Bulletin of the Geological Society of America

VOLUME 52 OCTOBER 1, 1941 NUMBER 10

CONTENTS

PAGES

Factors involved in submarine core sampling. By C. S. Piggot.... 1513–1524

Formation of igneous-looking rocks by metasomatism: a critical review and suggested research. By Frank F. Grout..... 1525–1576

Structural geology of the Knife Lake area of northeastern Minnesota. By John W. Gruner..... 1577–1642

Eruptivity and mountain building. By Bailey Willis and Robin Willis 1643–1684

Gravity coring instrument and mechanics of sediment coring. By K. O. Emery and R. S. Dietz..... 1685–1714

Subscription, $10 per year.

Publication Office: Florida Avenue and Eckington Place, Washington, D. C.

Communications for publication should be addressed to The Geological Society of America, Dr. H. R. Aldrich, Secretary, 419 West 117th Street, New York, N. Y.

NOTICE.—In accordance with the rules established by the Council, claims for non-receipt of the preceding number of the Bulletin must be sent to the Secretary of the Society within three months of the date of the receipt of this number in order to be filled gratis.

Entered as second-class matter in the Post-Office at Washington, D. C., under the Act of Congress of July 16, 1894.

Accepted for mailing at special rate of postage provided for in Section 1103, Act of October 3, 1917, authorized on July 8, 1918.

PRESS OF JUDD & DETWEILER, INC., WASHINGTON, D. C.

PAPERS IN PRESS FOR FORTHCOMING ISSUES

Geological Observations in the Lebanon Mountains of western Asia. By H. E. Vokes.

Igneous Rocks of the Highwood Mountains, Montana. Parts II-VII. By E. S. Larsen, B. F. Buie, C. H. Burgess, and C. S. Hurlbut, Jr.

Nondepositional Physiographic Environments off the California Coast. By F. P. Shepard.

Origin of Haleakala Crater, Maui, Hawaii. By Harold T. Stearns.

Stratigraphy, Structure, and Petrology of the Mt. Cube Area, New Hampshire. By Jarvis B. Hadley.

Genesis of some Ore Deposits of Southeastern Maine. By Ching-Yuan Li.

Permian Lime-Secreting Algae from the Guadalupe Mountains, New Mexico. By J. Harlan Johnson.

Structural Features of the Keewatin Volcanic Rocks of Western Quebec. By M. E. Wilson.

Geologic History and Correlation of the Jurassic of Southwestern Oregon and California. By N. L. Taliaferro.

FIGURE 1. VERTICAL SURFACE PREPARED FOR REMOVAL OF MATERIAL

FIGURE 2. MATERIAL BEING REMOVED IN BRASS TRAY

METHOD OF SECURING UNDISTURBED VARVES FOR REFERENCE

BULLETIN OF THE GEOLOGICAL SOCIETY OF AMERICA
VOL. 52, PP. 1513-1524, 3 PLS., 3 FIGS. OCTOBER 1, 1941

FACTORS INVOLVED IN SUBMARINE CORE SAMPLING

BY C. S. PIGGOT

CONTENTS

Page

Abstract 1513
Introduction and acknowledgments 1513
Deep-water sediment coring 1514
Description of factors involved 1514
Experimental procedure 1515
Discussion 1517
Summary 1523
Works to which reference is made 1523

ILLUSTRATIONS

Figure Page

1. Diagrammatic representation of the relation between core length, core penetration, and instrument penetration 1516
2. Distortion compared with core length expressed as a fraction of the whole 1520
3. Relation of core depth to sediment depth expressed as a function of the fractional depth in a core 1521

Plate Facing page

1. Method of securing undisturbed varves for reference 1513
2. Effect of bit on clay layers during penetration 1518
3. Distortion of core sample 1519

ABSTRACT

The unconsolidated condition of deep ocean-bottom sediments and their remoteness from the operator place definite limitations upon the design of apparatus and the technique of obtaining core samples of them. The varved clays of glacial lake bottoms, while not identical with deep-ocean sediments, are sufficiently similar to warrant some comparisons and provide a means of estimating the factors affecting the validity of a core taken from the ocean bottom. Tests indicate that cores are not so long as the instrument penetration but that they contain material from depths greater than the core length. Relationships have been established that indicate the corrections that must be applied to an ocean-bottom core and require only the measurement of the core itself.

INTRODUCTION AND ACKNOWLEDGMENTS

A core sample of any geological formation should represent identically the material being sampled. This is attained satisfactorily wherever the formation is strong enough to permit a rotary drill to cut away the surrounding material and leave a self-supporting core, but in deep-water core

sampling this condition does not exist. So far as is known, all deep-water sediments are unconsolidated near their surface and are incapable of self-support, and a rotary drill rig for rock would be impossible for all practical considerations.

Thanks are extended to Mr. Ellis Johnson for co-operation in securing the varved samples, to Dr. Wm. D. Urry for assistance in preparing the manuscript, and to Dr. Juul Hvorslev for helpful criticism and discussion.

DEEP-WATER SEDIMENT CORING

All deep-water coring techniques have the common feature of pressing a tube into the sediment, and whether this be done slowly or rapidly, continuously or intermittently, the material inside the tube is more or less disturbed and may be changed from its original position. The factors are the same as those involved in soil sampling for engineering purposes (Hvorslev, 1940), but the evaluation of their significance is further complicated by the impossibility of making adequate comparisons beneath great depths of ocean water.

DESCRIPTION OF FACTORS INVOLVED

The changes may be broadly classified as (1) distortion and (2) alteration. The first comprises shortening of the sedimentary column inside the sampling apparatus, *i.e.*, the core, and any change in the relative position of strata or other parts of the sample. These latter are caused by the friction between the core and the walls of the tube and, occasionally, by turbulence due to obstructions to free entry of the material.

Alteration involves those changes in the character of the sample due to squeezing out of water or the rearrangement of the constituent particles by the shock of the penetration of the sampling apparatus. These changes affect the application of soil-mechanics to foundations and other structures but have not yet become important in studies of ocean-bottom sediments.

The most important consideration in these studies is the shortening of the core in relation to the sedimentary column, and this is of the utmost importance in evaluating rates of sedimentation (Piggot and Urry, 1941), or the development of a time scale, or the relations of different events as revealed by the stratigraphy.

This shortening produces several uncertainties:

(1) Is it a true compaction, *i.e.*, pressing together of the material comprising the core?

(2) Is this shortening uniform throughout the length of the core, or does it vary with the strength of the several strata penetrated?

(3) Is it progressively greater as the tube penetrates into the sediment?

(4) The compaction may be only apparent and actually due to a thinning of layers by lateral displacement ahead of the tube, and this thinning may be progressively more pronounced as penetration proceeds, thereby producing a sample whose lower portion represents greater penetration than does the upper part.

(5) How much of the sedimentary column does a core represent? Does the length of the core define the depth of penetration of the tube?

(6) What are the numerical values of all these interrelated changes?

EXPERIMENTAL PROCEDURE

Obviously these factors could not be studied under thousands of feet of sea water; and, since they probably possess values peculiar to each locality, it seemed wiser to secure a generalized evaluation as accurately as possible, on land. For this purpose the varved-clay deposits of glacial-lake bottoms of the Connecticut River valley were chosen not only because they have been enumerated by Antevs and are easily accessible at several places but also because they provide definite increments which are easy to measure. The pit of the Pleasant Valley Brick Company, East Windsor Hills, Hartford, Connecticut, was used. In association with Mr. Ellis A. Johnson, of the Department of Terrestrial Magnetism of the Carnegie Institution of Washington, who was interested in the "fossil magnetism" of these same clays, a number of experiments were carried out whereby cores were obtained by various methods and compared with a sequence of the same varves in completely undisturbed samples. The latter were obtained by preparing a vertical surface extending down into the clay deposit from which overlapping sections were removed in trays 2½ inches wide by 30 inches long. These were later photographed at full scale and the photographs assembled to form a continuous record of all the varves used in the comparisons with the cores.

The procedure is illustrated in Plate 1, which shows a prepared vertical surface and the U-shaped brass tray, containing the sample for magnetic studies, being removed therefrom. Cores were secured from the immediate vicinity of the tray samples. These were obtained in various ways: by shooting the bit in quickly, by pressing it in slowly, by tapping it in a few centimeters at a time, and by using the thin-walled brass sample tube alone in these several ways. All the cores obtained by shooting with a 2-inch diameter tube were of nearly the same length. The cores were divided longitudinally and also photographed at full scale. The long strips of the respective photographs

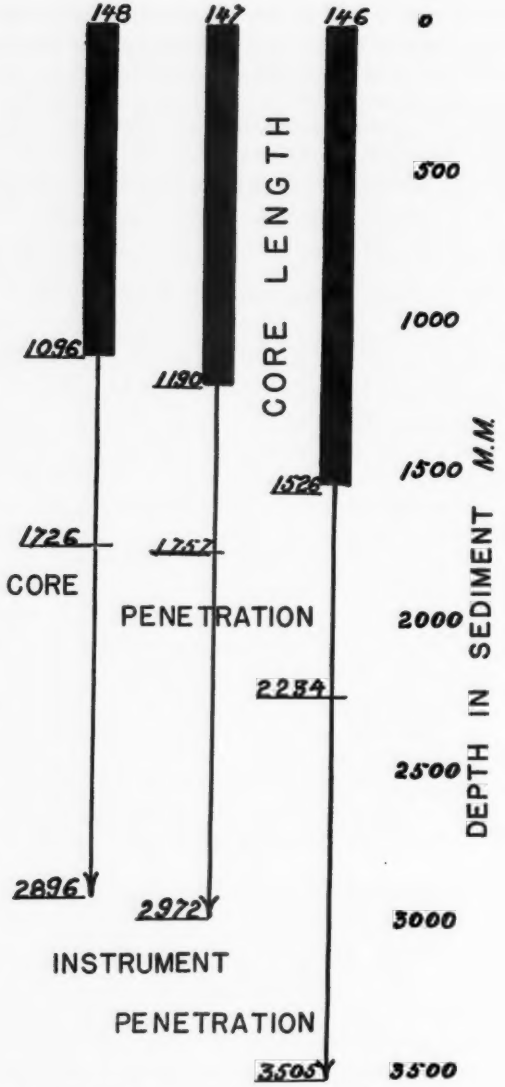

FIGURE 1.—*Diagrammatic representation of the relation between core length, core penetration, and instrument penetration*

were then arranged side by side, and the varves were matched and compared directly. The distortion of the cores was immediately apparent and was easily measured—not only the over-all length but also the thinning of the individual varves at different depths in the core.

The relations resulting from shooting the bit deep into the clay are illustrated in the diagram of Figure 1, which represents three cores selected because of differences in length. It was found, as a matter of practical experience, that in this material, and by analogy, in any particular material, all the cores taken with the same apparatus will be of substantially the same length. The reason for this will be discussed later.

The diagram (Fig. 1) shows that a column of clay layers 3505 mm. deep was penetrated by the bit. This was the greatest depth reached by the cutting shoe of the instrument. This depth may be called the instrument penetration. The core length is the length of the core actually obtained. These two dimensions are obvious, but there is another factor of the utmost importance which cannot be evaluated by examination of either tube or core, and that is the actual depth, in the sedimentary column, where material ceases to enter the tube. This factor may be called the core penetration. It is greater than the core length and less than the instrument penetration. In the three examples illustrated, the cores were 1096, 1190, and 1526 mm. long, respectively, but they contained material which was at 1726, 1757, and 2234 mm. below the surface in the undisturbed sediment.

The bottom of each core was found at the bottom of the tube, having been forced down to the limit of instrument penetration together with the bit. From the limit of the core penetration to that of the instrument penetration, the tube and its core behaved like a solid rod, merely displacing the layers of sediment as it proceeded.

DISCUSSION

When the sample enters the tube it adheres more or less to the wall of the tube and thereby builds up an increasing resistance to the entrance of more material. This produces a bulb of compaction in front of the advancing end of the tube, which presses material laterally as well as in advance of the tube. Eventually this internal resistance equals the strength of the material being penetrated, and the material directly in front of the instrument is forced aside, and no more enters the tube. Since this varved-clay (as well as submarine) material is saturated, it is essentially incompressible, and therefore there can be no change in volume. The thinning of the layers is due to lateral flow. The bit, however, may continue to penetrate the sediment for a considerable distance, taking the core along with it.

Figure 1 of Plate 2 shows the clay dug away from a bit which was tapped down 10 mm. at a time. After each 10 mm. of bit penetration the level of the clay inside the tube was measured with reference to the top of the tube, thus determining the sample increment which had entered the tube. When this had been reduced to 15 per cent the driving was stopped. Therefore this picture shows conditions at the time when material had almost stopped entering the tube. At the surface a bulging-up around the bit may be seen, and along the side of the bit a bending-down of the layers is apparent. Figure 2 of Plate 2 shows the condition produced by slowly pressing a thin-walled tube into a glacial deposit of sandy silt near Woods Hole, Massachusetts. This photograph and the information pertaining to it were kindly supplied by Dr. Juul Hvorslev, Research Engineer for the Committee on Sampling and Testing, Soil Mechanics and Foundations Division, American Society of Civil Engineers. The lower portion of the core has been split and replaced at its position of instrument penetration. The dark band in the core can be identified with the similar band about midway of the photograph (26 inches on the rule). Two inches below this band, material ceased to enter the tube, and all was dispersed away from the advancing tube and its load of core. The region of distorted material may be seen to extend a considerable distance below the bottom of the tube. This distortion is not quite so extensive when the bit is shot quickly into the sediment.

What was occurring inside the sample tube in the meantime is illustrated in Figure 1 of Plate 3. At the very top the layers are probably not thinned at all, but this effect soon begins, as is shown by the compaction of the five varves, Numbers 3300 to 3305. Around the side they are bent down by the drag of the wall of the tube as it slides by. Near the bottom, however, the layers are considerably thinned and bulged downward within the sample by the advancing bit and its load of core. The bit cuts through these thinned and curved layers and adds them to the core sample. Their thinning and curvature are in striking contrast to the same undisturbed varves on the left. It is obvious that a specimen, of a certain length, removed from this part of the core represents more of the original sediment, and probably a longer interval of time, than one of the same length selected from the top of the core. The thinning is accomplished by displacing material laterally, and it is evident that a weak layer situated between two stiff ones would suffer more change than the latter and might be squeezed out almost entirely.

A material of uniform stiffness should build up this resistance continuously, as penetration proceeds, and thereby produce progressively shorter increments of core length with each unit of penetration, but should a weaker layer be encountered, as for example a stratum of very

FIGURE 1. BIT IN CLAY NEAR LIMIT OF CORE PENETRATION

FIGURE 2. DETAIL SHOWING DISTORTED LAYERS IN FRONT OF AND ALONGSIDE OF BIT

EFFECT OF BIT ON CLAY LAYERS DURING PENETRATION

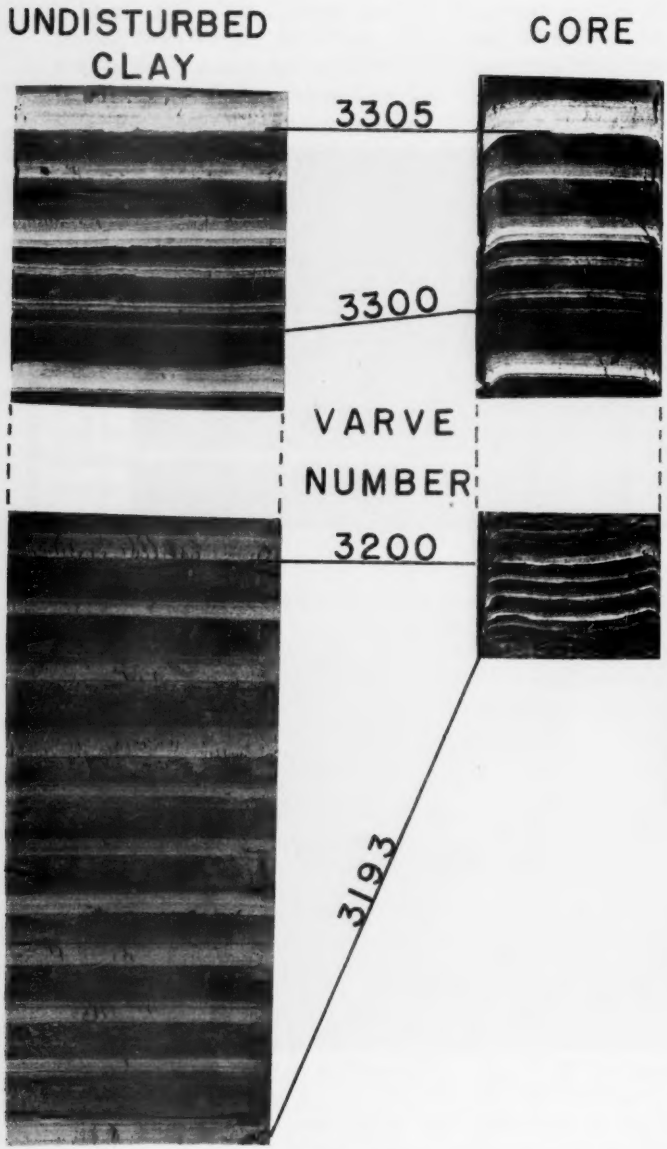

FIGURE 1. CORE MATERIAL
Showing distortion near top and bottom compared with the same layers of undisturbed sediment.

FIGURE 2. THREE TYPICAL VARVED-CLAY CORES
Compared with the undisturbed column of varves.

DISTORTION OF CORE SAMPLE

soft clay or loosely packed silt, this might be pressed aside entirely and no sample of it enter the tube at all (Pratje, 1934).

A very special case would be one in which the consolidation, and therefore the strength of the sediment, increases in exact proportion to the increase of resistance to material entering the tube. This particular situation would presumably provide equal increments of core length for the same unit of penetration of the tube.

The practical method of securing a longer core is to reduce the friction between the core and the walls of the sample tube and also between the outside of the bit and the sediment through which it is passing. This may be accomplished by decreasing the diameter of the cutting edge of the hardened-steel cutting shoe attached to the bottom of the bit and by increasing its outside diameter beyond that of the bit tube.

The core then enters the sample tube with an annular space between it and the inside of the tube. The stiffer or stronger the material being sampled, the slower will be its slumping and lateral expansion to the walls of the tube, and this is true also for the exterior of the bit. In the meantime the bit will have proceeded farther into the sediment.

Another factor which influences both penetration and core length is the "stickiness" of the material. The term is sufficiently suggestive without further definition, which would include viscosity, elasticity, colloid content, chemical composition, and other things equally difficult to evaluate. This stickiness reduces both instrument penetration and core length and in deep-water sounding is an important factor in the strain on the long sounding line at the time of pulling the instrument out of the bottom.

However, there is a limit to the reduction of the diameter of the cutting edge in relation to the diameter of the sample tube. The greater the annular space to be filled, the more slumping and distortion of the core will occur, and eventually a condition will be reached whereby the core does not grip the sides of the sample tube with sufficient strength and is sucked out again when the bit is withdrawn from the sediment. Various valves at the top of the tube have been tried but are impractical at the high velocities attained when shooting the bit into the bottom.

In practical deep-sea sounding it has been found that all these factors may be dealt with, in any particular bottom, by the use of a series of cutting shoes whose cutting edges have progressively smaller diameters. To secure the longest possible core from a particular bottom, the instrument is sent down with the powder charge adjusted to produce maximum instrument penetration and also progressively to decrease the cutting-edge diameter until the sample is lost, thereby establishing a diameter which is too small. The previous (larger) diameter then establishes the

longest core which can be obtained from this particular bottom. Progressively longer bits are used if necessary.

The general characteristics of the glacial-lake clays are quite similar to those of many deep ocean sediments, particularly the various oozes

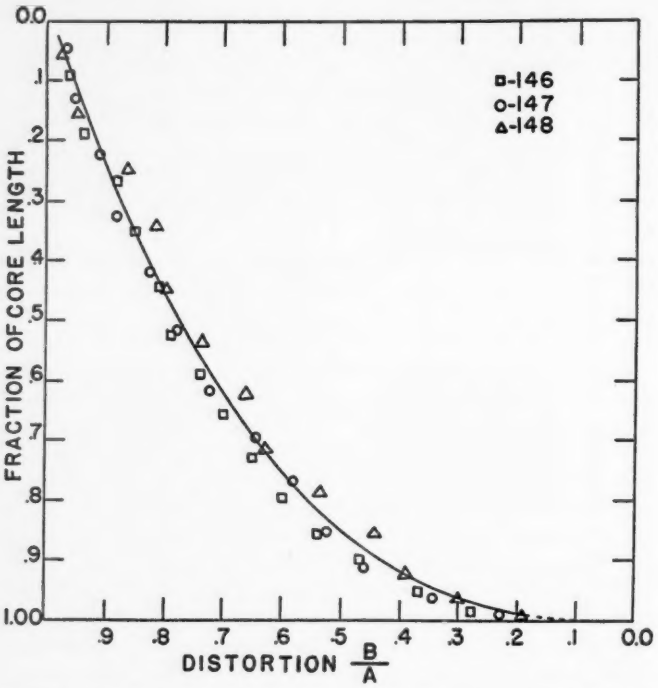

FIGURE 2.—*Distortion compared with core length expressed as a fraction of the whole*

and the Red clays, so that factors evaluated for cores from these clays may be regarded as indicating those which should be applied to cores taken from deep ocean-bottom sediments.

Figure 2 of Plate 3 shows three cores arranged adjacent to the undisturbed column of clay and demonstrates how the varves may be matched for comparison. The left-hand core is matched near its top with varve No. 3270 of Antevs' enumeration, and the last varve to be represented in the core is No. 3130, which occurs considerably farther down in the undisturbed column. The same applies to the other two examples. All

these cores were carried down bodily below the deepest varve secured in each case. By beginning at the top of a core and measuring the depths of a few varves and comparing these with the depths of the same undisturbed varves, the amount of distortion at any given part in the core, or its cumulative effect, may be evaluated.

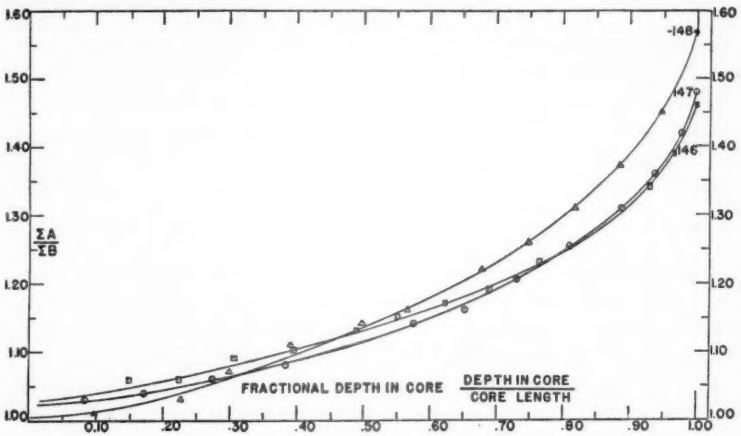

FIGURE 3.—*Relation of core depth to sediment depth expressed as a function of the fractional depth in a core*

The graph expressing these relationships for three cores is shown in Figures 2 and 3, and the data used for the curve of core P-146 are given in Table 1.

Figure 2 shows the extent of distortion expressed as the ratio of the thickness of a group of varves in the core to that of the same group of varves in the undisturbed sediment. This is plotted as the abscissa, while the ordinate is the mean position of the same groups of varves (varve increments) divided by the core length. Thus each mean position is defined as a fraction of the total length of the core in which it occurs. Since the only dimensions available for measurement in the case of a deep-sea core are its total length and the position of any particular stratum in the core itself, it is more useful to express this position as a fraction of the core length from the top of the core downward. Cores vary in length, owing to many factors, as has been explained, but Figure 2 indicates that the amount of distortion in cores of the same diameter, taken from material similar to this clay, is of the same order of magnitude for any certain fractional depth in a core where the instru-

TABLE 1.—*Relation of varved clay core P-146 to undisturbed varved clay*

Varve year	Increment mm		Mean depth of increment in core	Mean depth as fraction of core length	Core varves / Undisturbed varves = B/A	Depth of undisturbed varve Sum of A	Depth of varve in core Sum of B	Depth of varve as fraction of core length	Sediment depth / Core depth ΣA/ΣB
	Undisturbed varves A	Core varves B							
3275									
	51	44	22	.....	....				
3270						51	44	.....	....
	187	180	134	0.088	0.96				
3260						238	224	0.147	1.06
	122	115	282	0.185	0.94				
3250						360	339	0.222	1.06
	143	126	402	0.263	0.88				
3240						503	465	0.305	1.08
	160	136	533	0.349	0.85				
3230						663	601	0.394	1.10
	176	143	673	0.441	0.81				
3220						839	744	0.488	1.13
	131	103	796	0.522	0.79				
3210						970	847	0.555	1.15
	136	100	897	0.588	0.74				
3200						1106	947	0.621	1.17
	150	105	1000	0.655	0.70				
3190						1256	1052	0.689	1.19
	173	112	1108	0.726	0.65				
3180						1429	1164	0.763	1.23
	150	90	1209	0.792	0.60				
3170						1579	1254	0.822	1.26
	171	93	1301	0.853	0.54				
3160						1750	1347	0.883	1.30
	156	74	1384	0.907	0.47				
3150						1906	1421	0.931	1.34
	148	55	1449	0.950	0.37				
3140						2054	1476	0.967	1.39
	180	50	1501	0.984	0.28				
3130						†2234	*1526	1.000	1.46

* Core length.
† Core penetration.

ment penetration exceeds the core penetration. Figure 2 shows that a sample taken from the midpoint of such a core is only about 79 per cent as thick as it was in the undisturbed ocean floor, and that near the bottom of such a core the sample may be only 20 per cent as thick as the sediment it represents. This is of great importance in investigations where rates of sedimentation or time intervals are significant.

Figure 3 shows the relation of any point in a core to its original position in the sediment plotted from the data for three typical cores, again expressed as a fraction of the length of the core in which it occurs.

Although these data were obtained from material which is not a deep-sea sediment, they are thought to represent at least the order of magnitude of similar factors in deep ocean bottoms and they provide the only numerical corrections now available.

It should be emphasized that this discussion applies to a sample tube of $1\frac{15}{16}$ inches internal diameter, with a shoe whose cutting edge is of the same diameter, and to the case where this tube is forced into the soil by means of shooting or other methods producing a fast, uninterrupted penetration of the tube. However, these dimensions apply to all the ocean-bottom cores secured by the Geophysical Laboratory to date.

SUMMARY

The differences existing between a core sample and the unconsolidated marine sediment it represents are discussed and are evaluated by comparison with available material of more or less similar character, for one type of sampling apparatus which has secured cores from the ocean bottom at depths of more than 16,000 feet.

The length of such cores is not a measure of the instrument penetration, and they contain material which lay more than the core's length below the surface. Graphs are provided which suggest corrections that should be applied to both the thickness of a specimen from the core and its proper position in the bottom in order that it may be adjusted to conform with the original sediment.

WORKS TO WHICH REFERENCE IS MADE

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Piggot, C. S., and Urry, W. D. (1941) *Radioactivity of ocean sediments. IV. The radium content of the sediments of the Cayman Trough,* Am. Jour. Sci., vol. 239, in press.

Pratje, O. (1934) *Sind die Bodenprofile aus den Rohrenloten ohne Unterbrechungen?* Annalen Hydrographie u. Maritimen Meteorologie, vol. 62, p. 129.

Geophysical Laboratory, Carnegie Institution of Washington, Washington, D. C.
Manuscript received by the Secretary of the Society, March 19, 1941.

BULLETIN OF THE GEOLOGICAL SOCIETY OF AMERICA
VOL. 52, PP. 1525-1576, 1 PL., 4 FIGS. OCTOBER 1, 1941

FORMATION OF IGNEOUS-LOOKING ROCKS BY METASOMATISM: A CRITICAL REVIEW AND SUGGESTED RESEARCH[1]

BY FRANK F. GROUT

CONTENTS

	Page
Abstract	1525
Introduction	1526
Statement of the problem	1527
Difficulties of the problem	1528
Definitions of terms	1530
Suggested research	1540
Specifications for a satisfactory report	1540
Schedule of criteria of metasomatic replacement	1541
Applicability of these criteria of metasomatic replacement	1543
Other field and laboratory specifications	1554
Calculations and assumptions	1556
State of the replacing fluid	1560
Discussion of data	1561
Method of presentation of results	1563
Concluding statement	1568
Bibliography	1569

ILLUSTRATIONS

Figure	Page
1. Sketch of a hypothetical intrusive into steeply tilted beds of uniform strike	1545
2. Structure of the French River area	1546
3. Structure of an area in Columbia quadrangle, South Carolina	1547
4. Diagram of transition from metasediments to intrusive, Inyo Range, California-Nevada	1548

Plate	Facing page
1. Quartz mosaics in igneous rocks	1544

ABSTRACT

Many granites pass by insensible gradations into schist, quartzite, or other metamorphic rocks. There have been numerous suggestions that the granite at

[1] A collection of notes on this subject was begun by the Committee on Batholiths of the National Research Council. After several years of co-operation and exchange of ideas, criticism, and discussion, the writer cannot always be specific in giving credit for certain ideas, but many are here presented which were no doubt contributed by the other members of the committee. Very helpful comments have been given by Robert Balk and A. F. Buddington. The writer, however, should be held responsible for the statements in their present form. Some use has been made of a class report by Lowell Moon.

such places resulted from metasomatic replacement of older rocks, but it is hard to find a really conclusive large example that has been described in detail. Several well-known papers are here given critical comment.

The problem is difficult for many reasons, and reconnaissance no longer suffices as a basis for the suggestion of large-scale metasomatic origin. It is hoped that one or more of the promising districts may be given very thorough study and careful discussion to provide a type to which others may be compared. The features of a good report to establish such a type are described in some detail. Until such a type district is found, considerable caution should be exercised by those who suggest metasomatic origin of igneous-looking rocks.

INTRODUCTION

At hundreds of places igneous rocks and metamorphosed sediments are associated and have been described as showing gradational rather than sharp contacts. The descriptions of facts are numerous, and it might seem that little could be added. Nevertheless the interpretations have been and still are so conflicting that it may be time to call for more detailed evidence. The literature is being flooded with suggestions of the origin of some granites by metasomatism. Holmes and Harwood (1937, p. 249) go so far as to suggest that "granite magma disappears as a fundamental postulate . . . . only the emanations and their associated energy remain."

This was an old controversy nearly half a century ago when Geikie remarked that it was curious to see how the oscillations of geological theory were reviving the views formerly held, but more recently abandoned, as to the metamorphic origin of granites. Barrell wrote (1918) under the heading of "the rise and decline of the metamorphic theory of granite," that up to 1860 granite was regarded as essentially intrusive, but gneiss as a metamorphic product mostly of sedimentary origin. T. Sterry Hunt then started a retrogression in geologic theory by advocating the formation of granite by metamorphism. Barrell said that after Lawson's work on Rainy Lake (1887)

> "the truly igneous nature of granite became increasingly accepted until now (1918) the notion of its being made of sedimentary rocks softened and recrystallized by the rise of isogeotherms through deep burial is as obsolete as the still older doctrine of the Neptunists that granite was laid down as a crystalline precipitate on the floor of the primitive ocean."

Lawson himself (1914) had referred to the doctrine as widely accepted "thirty years ago," but no longer favored. He made penetrating comments on accepting theories not yet established.

Nevertheless careful reading indicates that the theory was not a popular one from 1880 to 1927 (Johannsen, 1932). Some men first considered the idea favorably and then discarded it. (Gallagher, 1937, p. 14-15).

Even while these careful and thorough workers were thus attempting to "lay the ghost," a new vitality was injected into it, perhaps most

effectively by Sederholm, who wrote for the International Geographical Congress in 1913 a paper on granitization, including under this title a variety of processes. His followers have seized upon the word with such enthusiasm that many papers since 1928 [2] advocate some such process as probably forming igneous rocks. Butler (1940, p. 39) credits Quirke with giving the idea an impetus in America. It is popular now to try to apply the idea. This review is frankly critical, but it is hoped that the suggestions may be constructive and lead to some restraint and balancing of evidence.

Bailey Willis (1932) noted that it is commonly easy to marshall a large group of corroborative evidences for a suggested hypothesis and easy to find phenomena which the hypothesis will explain, but by the time a suggestion has been used as much as this one, it should have been subjected to careful tests and testing is difficult. It requires rigorous thinking even to devise such a test. This paper simply outlines a more careful study rather than a test to prove or disprove the hypothesis.

STATEMENT OF THE PROBLEM

Fenner (1933) has worded the problem probally as well as anyone, and the present writer is glad to quote his statement as a suggestion for which he has a very sympathetic feeling.

"There is a growing evidence and belief that some magmas commonly associated with lit-par-lit structures cannot be injections in the ordinary sense. The magma *plus* the country rock (which may be only a shadow) occupy the space once occupied by the country rock. Either there is melting down in place, or more likely something between a melting-in-place and a hydrothermal replacement has taken place. There must be some material added and some taken away. Does this indicate that hydrothermal solutions are followed near the magma by more and more concentrated solutions until the replacements are caused by a liquid with all the characteristics of a magma? Is it reasonable to assume that granite bodies of batholithic dimensions and with all the appearance of magmatic granites may actually be the result of replacement little by little?"

This wording of the problem does not present an example and does not advocate a metasomatic origin for a large mass of granite. It presents a problem in the hope that someone might solve it by description of a good conclusive example.

There are many evidences that granite magmas exist as liquid magmas, that they inject the crust as normal magmas, and are capable of forming such rocks as the "orthodox" magma should. Probably almost all geologists also agree that, near the igneous magmas, volatile constituents may emanate from the magmas, replace the adjacent rocks, and perhaps in some places make them look igneous. In any area of igneous rocks, then, a geologist should expect both igneous rocks and "igneous-looking"

[2] Average about one a year before that; about 20 in 1937.

rocks and try to discriminate. It is not, or should not be, his ambition to prove an "unorthodox" occurrence but rather to do an accurate piece of work on the quantitative relations of the two. The work requires detailed areal mapping by a man so thoroughly trained that he knows what to look for. His report should show not only positive evidence for his conclusions but some additional evidence that he was aware of alternate possibilities and had looked in vain for facts in their support.

Sederholm himself saw the complexity of the problem and was much more cautious in his remarks than some of his followers. He said he was satisfied if the reader could see the possibility of solving the problem if a detailed study was made somewhere. Recent writers have now suggested that igneous-looking rocks resulted from metasomatism in so many places that they assume the process is established, wholly fail to see the complexity of the problem, and quote each other as authorities but not one area has been described convincingly. It seems that the enthusiastic advocates carry their idea too far, applying it to masses several miles across; the conservatives admit a few feet; the truth may lie between, but the conservatives have the weight of evidence on their side, and the burden of proof is on the advocates of extensive granitization.

No reasonable scientist nowadays holds to hypotheses that can be disproved—proved wrong. There is much time, however, for scientists to consider hypotheses that, while they have not or cannot be proved right, have not been proved wrong. Geikie (1905) says

> "geology does not generally admit of a mathematical demonstration of its conclusions. They rest upon a balance of probabilities. But this balance is liable to alteration as facts accumulate or are better understood."

It is precisely because of this situation that geologists have attempted to keep an open mind to the "value of outrageous hypotheses." This open mind, however, should not degenerate into a blind acceptance of a popular fad. No one should accept an outrageous idea because of the many times recent writers have suggested it. Assertion does not constitute evidence; reiteration is not proof.

DIFFICULTIES OF THE PROBLEM

The first and almost insurmountable difficulty in proving that an igneous-looking rock resulted from the metasomatism of one that was not previously igneous-looking is that the more successful the process is, the more completely it destroys the evidence of the process by which it was formed. The more like igneous rock it becomes the less sign it shows of origin from any other kind of rock. Such an origin is necessarily evidenced by remote inferences and can be safely suggested be-

cause it is about as difficult to disprove as to prove. Only when we find and can definitely identify relict minerals and structures are we able to follow the progress of change and then it is not "igneous-looking." The conservative petrologist claims that the extensive rocks that look igneous *are* igneous (recognizing of course the contamination of many magmas, and migmatization), and the proponents of granitization have not in any case disproved that they are actually igneous. The adventuresome and radical maintain that some are formed by metasomatism, and the conservatives have not yet disproved this.

The difficulty of the problem is really enormous, and those who suggest metasomatic origin without thorough work are likely to fall into error. First, there is the complexity of igneous action and metamorphism, including many features not yet clearly understood. Secondly, the terms used in describing such processes and the resulting rocks are not well systematized or well defined. In the third place, the evidences of metasomatic origin of an igneous-looking rock cannot ordinarily be clear because the processes normally occur at great depths and the results may be modified by other processes before erosion brings the rocks to the light of day. There should be proof of metasomatism and its extent and the time of its action. Then there should be detailed mapping—so detailed that the interpretation of structure is clear; this requires exceptionally good exposures and prolonged study by men well trained in mapping structures. There should be extensive laboratory work—petrographic, chemical, and physical—as a basis for calculations as to what the changes were and what became of the original material. Finally, there should be a careful discussion by experts in the various branches of geology which might bear on the conclusions.

The difficulty is very greatly increased by the fact that there may be deformation during the solidification of the true igneous rocks, so that they have structures closely resembling those that would be expected if a schist or gneiss was largely replaced. Piezocrystallization (Weinschenk, 1916) may be very common, and the fact that deformation was at a magmatic stage is indicated by the associated massive aplites and pegmatites. This evidence has been given rarely if at all in connection with discussions of metasomatism and, while the possibility is clear, the process should not be assumed to be normal, or a theory built on the assumption that it is true. In the famous Killarney gneisses (Quirke, 1940) the present writer saw some late related pegmatites just as gneissic as the granites. Dynamic metamorphism has made it very difficult to distinguish injection gneisses and deformed granites from granitized sediment. Perhaps the best way to cover

that particular point is to say that piezo-igneous rocks really look metamorphic. The more foliated they are by deformation of already formed crystals the less igneous they look. The more massive they are, the more positive the geologist may be that they look igneous. Nevertheless, all recognize that many igneous rocks have primary foliation.

The difficulty is further increased by the fact that some geologists (Wegmann, 1938, p. 35) call the evident migmatites granite. Lit-par-lit injection gneisses are migmatites, and while the one constituent is almost universally considered igneous, the other is of earlier origin, more or less modified. The mixed rock should not be called granite, unless the igneous component largely dominates.

Another difficulty involves the question of whether the replacement was deuteric or metamorphic. A truly metamorphic replacement is not always easily distinguished in finished rocks from the rather extensive mineral and textural changes that seem to be normal in the late stages of igneous crystallization (Tatge, 1939). The change of early minerals in a magma by reaction with residual magma is here recognized, and its importance emphasized, not slighted. That process, however, modifies the minerals of a rock that would be "igneous-looking" without that process. It is not the subject of this paper. The question is whether a definitely sedimentary or metamorphic rock can be made to look igneous by metasomatism on a large scale.

DEFINITIONS OF TERMS

Magmatic: A first distinction should be made between rocks formed directly from magma and rocks that are products of solutions that are of magmatic origin. Rocks formed by cooling of magma are igneous rocks, but those from emanations from magma are not, even though it is agreed that the emanations are of magmatic origin. Since cooling magmas result in igneous rocks, the term "magmatic rocks" leaves the reader in doubt as to its meaning. Barth (1936) and Reynolds (1936) refer to magmatic solutions, G. H. Anderson (1937) to magmatic fluids, and Freeman (1938) to magmatic liquids, when the context indicates that they may have in mind solutions of magmatic origin; the terms might apply to magma itself (a liquid, a fluid, and a solution) and are therefore ambiguous. It is better to mention magma in one case, its emanations in another, and both where there may be doubt.

On the other hand the term igneous seems better restricted to magmas and rocks than to emanations. When A. L. Anderson (1934, p. 390) mentions "igneous material" impregnating quartzite the nature of the material is not definitely indicated.

One of the most explicit of the recent references to this difference is in the work of Fenner (1938) on the Yellowstone Park flows. Writing of the effects of rhyolite on basalt he says the effects are suggestive of the way batholiths granitize their country rocks, and he brings up the question of whether such action is magmatic or hydrothermal. In the exposures on Yellowstone River he finds (p. 1458) there is little doubt that the basalt was changed at high temperature or, as he says, at a "truly magmatic stage." At that stage, however, the changes in the basalt were probably accomplished (p. 1483) by "a volatile solvent that has vanished." In other words the change was not a magmatic reaction but a reaction with an emanation of magmatic origin. Probably both the fresh and altered rocks in Yellowstone Park should be called igneous. On the other hand, if a sediment were changed by the "volatile solvent that has vanished" so that the altered sediment looked igneous, the fact that the volatiles were of magmatic origin would hardly justify one in considering the altered rock igneous.

It may not be possible to determine the origin of every rock, and it is probable that there are transitions; but to avoid utter confusion and loss of meaning of terms, the distinction should always be attempted, and the doubtful rocks can then be given a special note.

The rocks most commonly noted as transitional are the pegmatites which most geologists consider igneous, even in small dikes and litpar-lit injections. They grade into silexites which are even more difficult to distinguish from aqueous rocks. To distinguish some rocks as "aqueo-igneous" is of no advantage, for if two kinds cannot be distinguished it would be still more difficult to distinguish three. Currier's term (1937) "hydromagmatic" and Hess' (1933) "hypohydrous," for effects of fluids with less water than ordinary hydrothermal solutions, may put the emphasis where they wish it to be, but the two writers give only very indefinite criteria for the recognition of material resulting.

It is not necessary here to argue whether the magma rich in mineralizers grades into the water solution or separates sharply. The recognized fact is that some water solutions are of magmatic origin. If agreement can be reached as to the criteria that indicate water solution, then the minerals and effects it produces are best called hydrothermal and not igneous. Earlier liquids are magmas and rest magmas, and the products of their consolidation are igneous rocks, with or without deuteric changes.

The common indicator that the fluid is no longer magmatic is the mineral chlorite (Gallagher, 1937, p. 75; Gillson, 1932, p. 576; A. Knopf, 1930); with that are commonly sericite, serpentine, and so forth. Opinions may differ widely as to their reliability as indications that the mag-

matic period is past and the hydrothermal begun (Bürg, 1931); and there may be a great tendency to apply the term hydrothermal to effects of rest magmas (Bastin, 1935; Gilluly, 1933; Chapman, 1937).

The problem is made more difficult by the fact that early emanations resulting from release of pressure may possibly resemble late residues from crystallization of anhydrous minerals. It is certain that both early and late emanations may carry mineral matter from the igneous magma to its roof and walls, but there is less certainty of a difference in the nature of the mineral matter in the two kinds of separates—both may carry alkalies (Fenner, 1940).

A problem related to this concerns the nature of lit-par-lit injection. A careful reading of Sederholm's papers on migmatites indicates that he considered lit-par-lit injection gneiss as a rock resulting from a mixture of schist and magma, not including a mixture of schist and the emanations from magma. Wegmann (1938, p. 307) seems to agree with Sederholm. Van Hise (1904) described the Black Hills schists with numerous dike injections of granite, which at a distance from the igneous rocks gave way to quartz veins. This is probably the gradation to expect. The emanations make a veined schist rather than a banded granite gneiss. Several writers, however, have recently attributed injection gneisses to emanations rather than to magma injections (Stark, 1935, p. 23, and his students; Freeman, 1938, p. 698; Van Bemmelen, 1939a, p. 24). Possibly a rest magma or pegmatitic late magma residue by differentiation is the most likely to produce injection gneisses, but, as here distinguished, these are still magmas and not emanations. Niggli (1938) refers to "Dämpfe und Lösungen" and describes effects of gas separation; others leave the nature of the added material equally uncertain. Probably the term migmatite should be restricted to rocks, one component of which was magma, not emanations. The difficulty of distinguishing between effects of magma and those of its emanations must be admitted. It led Perrin and Roubault (1938) to write of the "convergence of endomorphism and exomorphism."

Nor is it necessary here to argue whether the emanation is a gas (pneumatolytic) or a liquid solution. The physical chemists seem inclined to consider the effects as a result of gas separating from magma. But the volatiles once separated are no longer magma and, while they are of magmatic origin, the rocks they alter do not acquire a magmatic origin or become igneous rocks, as a consequence of attack by magmatic gases.

There are, to add to the confusion of ideas, some examples of careless usage. Freeman (1938, p. 685) mentions two "granite rocks," one of which is a gneiss and the other a quartz-diorite. Cannon (1937, p.

47) refers to gneiss areas in which granites predominate. Read and Phemister (1925, p. 28) refer to an igneous-looking rock but call it a gneiss.

Assimilation: Magmatic assimilation is an expression usually referring to the solution of wall rocks or fragments in the magma. It results in a *"contaminated"* magma. The terms have been used by one or two writers in quite the opposite sense—that of the assimilation of magma or its emanations by the wall rocks (Iwao, 1940, p. 45) (Belyankin, 1939) and contamination of wall rocks by the magma (Turner, 1937, p. 90). This can be justified by dictionary definition but is a very confusing usage in petrography. Perhaps it should be avoided because other terms, such as introduction and contact action, are available. Read (1927) notes that the term contaminated is being used for "all kinds of mixtures . . . of igneous rocks and country rocks." Quirke (1927, p. 762) refers to a quartzite feldspathized by assimilation. Magmatic assimilation may dissolve a quartzite but does not add feldspar to the solid rock.

Assimilation of wall rocks by magmas is a process which is much modified by the depth at which it occurs. At great depths it grades into a process of magma generation. To most petrologists this process seems so different from assimilation by magmas near the surface that it is certainly to be recommended that the term assimilation be avoided for the deep-seated generation of magma. In describing rocks of doubtful history note can be made of the transition from shallow to deep conditions. Eskola (Barth, Carrens, and Eskola, 1939, p. 377) describes a process of adding alkali silicates to rocks making them like granites, but it seems likely that this occurs mostly at depths characteristic of magma generation.

The proof that assimilation and contamination have occurred, and their distinction from differentiation, are not simple but commonly involve careful field and laboratory studies. Harker (1932, p. 302) says thin leaves of a schist "may be entirely assimilated and the true nature of the resulting composite rock is then to be perceived only by careful scrutiny." What could the most careful scrutiny disclose? Once the rock is assimilated it becomes part of the liquid magma, and no scrutiny would detect it in the products of magma crystallization, though certain minerals may strongly suggest contamination.

MacGregor (1937) describes granitization by "metasomatic reconstitution" (p. 471) and permeation of magma into hornfels (p. 483) and then remarks in final discussion (p. 486) that he tried to show the rock originated by "assimilation." As usually defined, assimilation is almost

100 per cent different from metasomatism. "Reciprocal reaction" may of course involve both metasomatism and assimilation. Read and others (1925, p. 36) refer to assimilation ". . . giving rise to streaky granite with replacement structure." It is not the assimilation which gives rise to replacement, though the two processes may be simultaneous.

Metasomatism is defined and discussed by Lindgren who, from his extensive work along such lines, was certainly qualified as an expert and authority in the matter. Those who have attempted to modify the definition or usage only add confusion and looseness to the subject. Metasomatism is

> "an essentially simultaneous, molecular process of solution and deposition by which, in the presence of a fluid phase, one mineral is changed to another of differing chemical composition"

(Lindgren, 1925; 1933). The process is molecular in the sense that molecules form but it is not always "molecule for molecule" nor "atom for atom" (Barth, 1936, p. 841-842), as in chemical reactions; it is, however, very commonly volume for volume. Neither does metasomatism form a glass nor effect a replacement of mineral by magma, though Holmes (1936, p. 411) and Backlund (1938a, p. 390) have used such expressions. As Lindgren notes, several geologists have attempted to restrict metasomatism to those changes that result in essential changes of rock composition (largely ignoring water and carbon dioxide)—"rock metasomatism as distinct from mineral metasomatism." Lindgren protests this emasculation of a much-needed term.

The point to Fenner's suggestion already noted is that metasomatism may result from the fluid called magma as well as from watery fluids and gaseous emanations from magma. Our particular problem is therefore complicated by the variety of fluids which may react upon a rock to make it over into an igneous-looking rock.

Replacement is a term used commonly in a technical sense to imply metasomatism, but, since it is also used in a popular sense to mean other processes, it is almost necessary to say metasomatic replacement or metasomatism when that process is in mind. There are those who vigorously maintain that batholiths are emplaced by "replacement" (rather than by displacing their wall rocks and roofs) without any thought of metasomatism, but with the idea of stoping, injection, and assimilation. Daly (1933) describes batholiths as having the appearance of replacing invaded formations, partly by stoping. Quirke (1927, p. 120-121) refers to replacement of two kinds—microscopic features, which are metasomatic, and "regional" features.

Gallagher (1937, p. 39) says the essential minerals of a granite "formed not as a series of successive crystallizations, but as a series of successive replacements." It is of such statements that Johannsen remarks (1931) that

> "the word replacement is sometimes used to indicate replacement in the late stages of consolidation—a reaction in other words—therefore a replacement only in a Pickwickian sense."

This leads to the discussion of the term *deuteric* for such late reactions. The deuteric changes in a mineral grain are admittedly common metasomatic replacements, but it does violence to logic to use that evidence in an attempt to prove that a batholith results from metasomatic replacement of a schist. Deuteric action covers alteration of minerals and textures by late- or end-phase magma. The definition is discussed at length by Singewald (1932).

Osborne (1927, p. 57) and Backlund (1938, p. 339) avoid a definite characterization of the process of replacement by saying "a process akin to metasomatism," or "similar to metasomatism."

As the amount of change increases and the activity of the fluid involved becomes more intense, metasomatism grades into processes of other character. By definition metasomatism starts with a mineral, normally a solid, and ends with a solid; and during the process the fluids that act on the solid should not be assumed to destroy the inherent solidity of the nonfluid phases. If the fluid isolates the grains of the solid and the whole mass becomes mobile the terminology at once changes. There is first a *rheomorphism* or plastic mobilization, and then an anatexis or syntexis, which results in a new magma or contaminated magma. These terms indicate contrasting processes even if there is a transition from one to the other. A mineral mass cannot remain solid if liquid. It cannot be a metasomatic process that makes a rock become fluid magma.

The confusion of metasomatism (in solid) and assimilation (in liquid) no doubt arises from the fact that solids in the process of being replaced are permeated by liquid and strewed into the liquid, so that solution and replacement may be simultaneous. Eskola (Barth, Correns, and Eskola, 1939, p. 377) says the formation of migmatite is largely metasomatic. The making of a migmatite is a process of mixing, independent of replacement; but again it is likely that the two are simultaneous. At first thought this stage of attack might seem to deserve a special name; but it is at once apparent that the criteria for determining that stage will be almost impossible to find. It may be possible to prove that both metasomatism and assimilation occurred but not possible to prove that they were simultaneous rather than successive processes. The best way to de-

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scribe such effects is by use of the two terms, with the difference between them clearly in mind. It is wholly improper to say that the end result of metasomatism is magma; or that assimilation changed a hornfels to a diorite; or that assimilation granitized an inclusion. Tyrrell (1938) refers to

> "a vigorous controversy between the pure differentiationists, and the advocates of various degrees of assimilation aided by gaseous transfer processes. What may be called the Durham school, led by A. Holmes (1936) and D. L. Reynolds (1936; 1937) advocate a theory of *metasomatic origin* of many igneous rocks through processes *involving the mobilization* of country rock by gaseous emanations from magmas of ultrabasic composition" (writer's italics).

Reynolds (1937, p. 268) explicitly writes "Magma was actually developed as a result of the process," apparently referring to a process of progressive metasomatism. Tyrrell does not give his opinion as to the processes, but the expressions in italics seem contradictory. Metasomatism occurs in a solid, and mobilization is not a result but another process, not metasomatic.

Quirke and Collins (1930, p. 95), under the heading "metasomatic", cite rocks so completely altered that they intrude and invade other rocks. Backlund (1938b, p. 191) says

> "Da die Granitisation eine gewisse Kulmination der Metasomatose bedeutet, die in der Mobilisation (Rheomorphose) ihren definitiven Ausdruck findet. . . ."

Backlund (1938a, p. 380) also remarks that the emplacement process of rapakivi granite presupposes complete solidity of the rock traversed but in the rest of his description (p. 358, 360) he refers to the solidification process and (p. 390) to glassy textures. MacGregor and Wilson (1939, p. 210) believe that the work of Read and of Sederholm demonstrates that metasomatism may produce mobility. Harris (1937) refers to a hornfels mobilized by metasomatism. Other writers appear to have the same idea but they have not clearly defined their terms in a way to justify it.

In metasomatism a new mineral grows in the body of the old mineral or aggregate. If an added fluid or melt makes the mass viscously rheomorphic it is not "in the body of a mineral." If the aggregate grows mobile it is no longer an aggregate, but by its mobility the aggregate has been disaggregated. At once when it is mobile it becomes magma, and the process of adding liquid or melting is not metasomatism. Of course the liquid may still be reacting metasomatically with the minerals in it, but it is not metasomatism that makes an aggregate mobile—it is added fluid and perhaps assimilation or solution or palingenesis. The term *transfusion*, used by Holmes (1936) and by Reynolds (1936) in connection with the metasomatism and mobilization, may perhaps be intended as a general term to include both processes.

Ultrametamorphism is a term that many writers on these subjects find convenient. Sederholm (1926, p. 86) similarly refers to ultrametasomatism. If metamorphism reaches a stage of fusion it should be considered magma formation, and the rocks produced are no longer metamorphic but igneous. The difficulty arises from the fact that fusion is a gradual and progressive process in most rocks, and if a rock is partly fused it may retain enough original mineral or structure to be considered metamorphic. No one seems to have accurate estimates as to the percentage of fusion in highly metamorphosed rock, and it seems quite impossible to base a distinction in nomenclature on the proportion of rock liquefied. The term ultrametamorphism should probably be almost equivalent to rheomorphism, in which clear evidence of an original rock, either mineral or textural, is accompanied by evidence of liquid flow. Such evidence is not easily obtained, because solid rocks also flow, and the evidences cited for rheomorphism in an igneous rock are almost duplicated in marbles which have rarely been suspected of liquid flow.

Granitization is a term much used in the discussion of the origin of igneous-looking rocks. It is the subject of a paper by Sederholm (1913b) and of a review with new discussion by MacGregor and Wilson (1939). In numerous recent papers, the term granitization has been practically ruined by loose usage. This is serious because the casual reader (as distinct from the careful, technical petrologist) wholly misunderstands the term granitization, thinking that some other rock has been "turned into granite" by metamorphism. This is far from the meaning of most who use it.

In the recent revival of discussion and use of this term Sederholm is commonly credited with "setting the pace," but in the 1913 paper and several others he defined only by illustration.

A keen analysis of the difficulty of defining terms was offered by Johnson (1938):

> "The very great difficulty of defining a scientific concept in terms which shall be sufficiently conclusive and at the same time sufficiently exclusive to defy criticism, is too well known to require emphasis."

An example is Davis's concept of the profile of equilibrium, for which he never gave any concise definition; and an attempt to frame a definition might be misleading.

> "The only safe procedure is to go back of each writer's definition of a concept and get from a fuller reading of his published works as complete a picture as possible. . . ."

The following paragraph may serve in Sederholm's case, but his writings are so voluminous that there is no certainty that all his ideas on that term can be condensed into a short paragraph.

Sederholm's double title, "Regional granitization (or anatexis)," leads to a first idea of its nature—granitization includes an ultrametamorphic process in which deep-seated rocks are remelted by heat and hot gases from below, thus providing regenerated magmas *in situ*. His next example is "penetration" near granite—an aplitic magma has been intruded along the broader fissures and has been absorbed through capillary openings in the schist. The aplitic magma "intimately permeates the rocks." The effects are referred to as "contact phenomena." He next describes granitization in rocks adjacent to a granite; the older rocks are

"brecciated . . . and cemented by granite which occurs partly as well separated veins, and partly as a constituent of gneissic migmatites."

Then there are breccias with fragments soaked and partly assimilated in magma; then ptygmatic folded dikes in older rocks; then the evidences of palingenesis of several rocks—leptite, schist, and conglomerate. Finally he groups them all together in a closing paragraph as granitization. He thus included in the term lit-par-lit injection, arteritic injection, metasomatic replacement, ptygmatically folded dike injection, contact effects of granite, border brecciation by granite magma, assimilation of fragments, strewing of fragments in magma, migmatite formation generally, and refusion, palingenesis, or anatexis. He seems clearly to exclude magma generation (1907, p. 100) at great depths, though he includes palingenesis in the lithosphere.

In their recent comprehensive review, MacGregor and Wilson (1939) attempt to cover the ideas of Sederholm and others by including nine processes that can be named and yet are rarely well defined. In their discussion (p. 205) they add another process, recrystallization. In the summary (p. 212) they attempt a brief definition; granitization is "the process by which solid rocks are converted into rocks of granitic character"; but it is quite uncertain whether they mean the rock remains solid throughout the process or whether the granitization includes magma generation from an older rock and its normal crystallization to granite; and the expression "rocks of granitic character" is so loose that it may refer to (1) granitic composition regardless of structure and texture (p. 205, "inherited structure"), or (2) coarse texture and massive structure regardless of composition (p. 205, "recrystallized graywacke"), or (3) rocks to which granite magma has been added (lit-par-lit injection), or (4) rocks changed by emanations from granite magma, even if made less like granite than before (p. 207).

In any event the term as used by Sederholm seems to cover a wide variety of processes and results, nearly all of which seem to be in some

way related to granite magma or to some rocks receiving materials of a nature to make them more like granite than before. This cannot be said of all writers on granitization since 1913. G. H. Anderson (1937, p. 47) specifically recommends that the term include dioritization and gabbroization. Reynolds (1934, p. 600) says a sediment was "granitized" by a "hybrid augite-biotite-diorite". MacGregor (1938, p. 481) says "granitization includes all processes whereby pre-existing rock is converted to a quartz-dioritic product": as if the addition of andesine to a granite was granitization.

The followers of Sederholm have not all realized the wide variety of processes that Sederholm included. Backlund (1938c, p. 107) says Sederholm meant by granitization a process operating without removal of the sedimentary (or other sialic) mass as such and without the operation of melting or assimilation as usually understood. This cannot be read in Sederholm's 1913 paper, and the writer has failed to find it elsewhere. As examples of different usages, Fahlquist and Berkey (1934, p. 24) seem to believe that granitization is metasomatism, and they contrast it with "invasion, digestion and absorption"; whereas Van Bemmelen (1939, p. 134) uses granitization as if it includes rising emanations forming magmas; and Backlund (1936, p. 343-344) uses granitization as equivalent to "Magmaaufstieg," the process of magma rising in the crust. Lacroix attributed to "microgranitization" a rock that seems to be a chilled border.

Several recent advocates of granitization have been asked if *all* the effects of emanations from a granite should be considered as granitization, and the answer is always that those effects were at least the beginning of granitization. This covers a good deal, because at times CO_2 escapes from granitic magma and might turn the near-by silicates to carbonates; but it seems very far-fetched to consider that effect granitization. Probably the enthusiasts have extended the idea too far. When a geologist now says "granitization extends a few feet into the greenstone" (Bartley, 1939) no one can tell whether the rock for that distance (1) looks like granite, (2) is an injection gneiss, (3) is a contact breccia, (4) is a schist with feldspar or quartz metacrysts, or both, or (5) has tiny streaks of ankerite replacing it along the schistosity.

There are, in addition, examples of careless usage, but perhaps the term need not be criticized because of an occasional abuse. No progress in clear thinking can be made by the continued extensions of the meaning of the term. One can almost say it has no meaning, for no two papers seem to agree.

Under these circumstances it is suggested that geologists take one of the following positions: either (1) abandon the term and avoid using it,

realizing that there are plenty of terms that describe the effects more specifically, or (2) if the term is sure to be used, give it a definition strict enough to be intelligible. The second procedure seems best, because, as Fenner (1940) says, "granitization is probably accepted by most geologists as a common process." It would be systematic if the definition could be restricted to the production of those rocks which have been made to look like granite in minerals and texture; but this is so different from common usage that the change can hardly be hoped for. The writer would suggest that *granitization includes a group of processes by which a solid rock (without enough liquidity at any time to make it mobile or rheomorphic) is made more like granite than it was before, in minerals, or in texture and structure, or in both.* Discussion of such a definition is desired.

With this broad definition (and the even broader usage of other writers) it may be misleading to write of "the manner in which granitization has been accomplished" (Fenner, 1938, p. 1458), but all should realize that there are many processes by which it is accomplished.

Finally, it is clear that many of the processes of granitization do not make a rock look igneous (Holmes, 1918, p. 66; Goldschmidt, 1921, p. 81-91; Fahlquist and Berkey, 1935, p. 14-25) and so are outside the discussion of this paper, and many papers are so indefinite that it is impossible to tell whether the product is igneous-looking. Nevertheless many papers on granitization refer to metasomatism, and probably granitization has produced some igneous-looking rocks.

SUGGESTED RESEARCH

SPECIFICATIONS FOR A SATISFACTORY REPORT

It is the purpose here to suggest the specifications for a report on what may somewhere be found to be a convincing example of a large formation made to look igneous by metasomatic changes. The points to cover are numerous and rather difficult, and safe conclusions are not obvious from a brief study. Attention is called to the failure of some published papers to cover the required points not for the sake of being critical but in the hope that some example may be made more complete and convincing. On the other hand, if none can thus be made complete and convincing, the discussion should induce a certain caution in the continued suggestion of a process not yet proved after several generations of search.

In outline a satisfactory report should cover (1) a careful description of the igneous-looking rocks involved, (2) the criteria proving metasomatism—structural, textural, mineralogical, and chemical, (3) the scale of the operation, (4) the field and laboratory evidences as to what

was changed, (5) field evidences, calculations, and reasonable suggestions as to a source for the large amount of replacing material, and an equally satisfactory method of disposal of the replaced rock and replacing fluids, (6) a discussion that is not too partial in balancing the evidences for and against origin by metasomatism, and (7) all these items stated in terms clearly defined and without the tricks of a debater advocating only his favored idea. This list is elaborated in the following pages, but the discussion is not exhaustive, and additions, corrections, and suggestions will be welcomed. As Backlund says (1938c) the "strangeness or unfamiliarity of a . . . theory can never be regarded as evidence against it," but in presenting an idea that is not widely accepted one should expect to meet objections. The evidence for it should be such as to bear critical scrutiny of other workers. Each of the points mentioned in the outline should be covered in a way to stand critical study.

During the course of metamorphism the approach to igneous appearance may be gradual, and, if the process is interrupted, the outcrops may show stages of change, either mineralogically, or texturally and structurally, or both. The claim that the rock looks igneous cannot be made for the intermediate rocks in the series. It remains to pick the points to be observed and reported as evidence of metasomatism. The following schedule covers chiefly those criteria applicable to igneous-looking rocks but touches only lightly on others that might be important in ore deposits.

It is a serious question whether ordinary magmas circulate freely enough in capillary openings to cause extensive replacements, but, as that is the basis of many suggestions here referred to, the idea may be retained as a working hypothesis until evidence is more complete. Clearly the late rest-magmas do metasomatically replace early minerals formed in magmas, but these active rest-magmas are a small percentage of the volume of the original whole magma.

SCHEDULE OF CRITERIA OF METASOMATIC REPLACEMENT

A. *Textural and structural.*

(1) Pseudomorphs and partial pseudomorphic rims.

(2) Inherited and relict textures and structures. Preservation of rock or mineral textures and structures in rocks whose mineral or chemical composition does not originate with such textures or structures; such as silicified, bedded, fossiliferous limestone; propylitized andesite porphyry; sericitized granite; and garnet zones in calcareous sediments.

(3) A lack of evidence that the magma crowded or displaced its walls.

(4) Faceted crystals intersecting original structures and grains; the crystalloblastic series of form relations. Most important are feldspar porphyroblasts, especially if they are more abundant near granite than at a distance.

(5) Presence, in a rock of one origin, of minerals or textures of a different origin; such as coarse pyrite in a sandstone; or a corroded quartz phenocryst in fine quartz groundmass; or zircon in a carbonate matrix.
(6) Unsupported structures (except in igneous rocks); and even in igneous rocks, as in other deposits, inclusions or "islands," oriented as in "mainland" of country rock or larger crystals.
(7) The body suspected of replacing is related to fractures, or zones of fractures, or to certain beds of a series, or to an impervious barrier, or to a contact of a sediment and a truly intrusive rock.
(8) Apparent inclusions with zones of different minerals.
(9) Gradations to country rock and inclusions of it. This is best if a bed can be followed along the strike to one that looks igneous, and at intermediate points it shows petrographic signs of replacement.
  (a) Unaccountable "disappearance" of a great thickness of sedimentary rock.
  (b) Truncation of the foliation.
  (c) Nebulitic or ghost inclusions.
(10) Boundaries (if not gradational) are more or less irregular, rounded or saw-toothed, rather than scalloped with concavities in the country rock. Pipes and stringers may extend out from the main body of replacement.
(11) Large crystals contain inclusions of a mineral normally later in the igneous reaction series; such as hornblende with inclusions of quartz.
(12) Large excess of introduced material over porosity of original rock, with no sign of increased volume.
(13) Helicitic texture—schistose inclusions in porphyroblastic crystals.
(14) Diffusion banding, shearing, or residual bedding, in contrast to crustified banding.
(15) Great variety in sizes and forms of both the grains and the deposits as a whole.
(16) Abnormally large crystals.
(17) Clear crystals in a rock most of which is dusty.
(18) Great concentrations of rare rock constituents; such as lithium or beryllium.
(19) Myrmekite and myrmekitelike growths.
(20) In veins and ores the walls, even when not offset, do not commonly match; replacement gives "floating ice" as distinct from "exploding bomb" structures (Schwartz, 1927, p. 298, 302).

B. *Chemical.*

(21) Analyses of original and altered mineral aggregates (with data on porosity and specific gravity) may show, by calculation, any gains and losses. These differ in different examples, but soda is a common addition.
  (a) If there are both gains and losses, the change favors metasomatism. If the changes prove to be simple addition of magma or emanations, this is not much sign of metasomatism.
  (b) If material has been removed, it is desirable to suggest a reasonable explanation as to what became of it.
  (c) The changes may indicate the state and composition of the fluid involved in metasomatism.
(22) A series of analyses may show that the supposed original rock could form the igneous-looking product by progressive admixture of a solution of reasonable composition.

(23) Analyses may show that the igneous-looking rock is abnormal in a way that could be explained by a replacement of other rock.

C. *Mineral.*

(24) All hydrothermal or contact metamorphic minerals suggest metasomatism.
(25) Quartz and carbonates are very common; chlorite, epidote, sericite, serpentine, pyrite, garnet, albite, uralite, biotite, barite, and fluorite are not rare. Most primary igneous minerals (notably microperthite) are less common in replacements than in igneous rocks.
(26) Equal quantities of resistant accessories in the deposit and country rock.
(27) Albitization, chess-board albite, especially if the albite molecule is more than 95 per cent. The feldspars are less homogeneous than in rocks cooled from magma.
(28) The replacing material commonly selects certain original minerals of a complex and attacks one mineral after another in a sequence.
(29) Abundant epidote to exclusion of other mafic minerals.
(30) Bluish quartz.
(31) Ore minerals furnish a variety of other criteria.

APPLICABILITY OF THESE CRITERIA OF METASOMATIC REPLACEMENT

One of the common remarks about a schist that is believed to be "granitized" is that it has or has not a "true igneous texture." (Freeman, 1938, p. 691; Grantham, 1928, p. 318-319). The textures of igneous rocks are so numerous and look so much like metamorphic textures that the general remark can carry no weight. Details must be given. The textures and minerals must be studied in thin section, and even then the interpretations are difficult. Stark (1935, p. 23) wisely says

> "the microscope does offer much evidence of replacement . . . but it must be admitted that many of the features might be explained . . . by deuteric changes."

Others have noted that the data used to prove one side of the argument are not at all inconsistent with the opposing theories.

Specific examples of doubtful interpretation of textures are provided by quartz mosaics that remind some geologists of the texture of adjacent quartzites or sandstones. The present writer has seen in the red granite at Pigeon Point such a quartz mosaic that strongly suggests the inclusion of a small fragment of the overlying quartzite; but he has also seen approximately the same pattern in granites and dike rocks where field work indicates little chance of included quartzite. The same doubt has arisen elsewhere. Quirke (1927, p. 768) finds quartz grains in granite near Killarney, "supposed to be of the same origin" as quartz in clastic rocks; but Jones (1930, p. 50) finds in the same outcrops only granulated magmatic quartz. Horwood (1936, p. 108) and Stark (1935, p. 20) show photomicrographs of quartz in microcline, each reporting that microcline replaces earlier quartz, although the simultaneous extinction of quartzes, reported by each author, suggests a primary igneous intergrowth. Ander-

son (1934, p. 384, and Figs. 3-8) noted a quartz mosaic in the Cassia batholith.

Plate 1 shows the microscopic texture of quartzes in several rocks, which are so far from quartzite outcrops and which show so little evidence of contamination that the texture can hardly be attributed to quartzite inclusions. To claim that they are quartzite is to do violence to the evidence. Figures 1 and 2 of Plate 1 are from a thin section of a dike, cutting a granite of about the same composition as the dike; and most of the country rocks near the granite are dark schists with little quartz. The other figures are from Minnesota and Dakota granites surrounded by similar dark schistose country rocks. Such textures carry little weight as evidence of metasomatism or granitization.

Criteria 2 and 3: It is exactly because rock structures may be lost during replacement that it is possible to speculate on the sedimentary origin of an igneous-looking rock, but there is a marked shortage of detailed maps showing harmony in the structure in the country rocks and igneous-looking rocks that are supposed to result from their metasomatism. Small scale maps are common (Horwood, 1936; Kesler, 1936; Anderson, 1937), and several show hardly any structure symbols except the major contact lines. Even where the strike and dip are the same in the two rocks, the linear structures should be added before conclusions are drawn as to displacement or replacement. Figure 1 shows a displacement, though the foliation alone might suggest replacement.

Several writers in reporting structures refer to replacement but elsewhere in the papers give clear evidences of displacement, leaving the reader in doubt as to whether there was an error of wording or a lack of understanding of the structures seen (Kesler, 1936, p. 38-43; Horwood, 1936, p. 99, 100; and Fig. 1; G. H. Anderson, 1937, p. 10, 25, and Fig. 4; Read, *et al.*, 1925, p. 35; Read, 1939, p. 772, 774).

Criterion 4: The common formation of metacrysts in a schist near a granite contact has led to a surprising extension of this criterion by some writers. The contact zone may have metacrysts not only of garnet and other characteristic metamorphic minerals but even of feldspar and of quartz. These feldspars and quartzes so closely resemble the phenocrysts of quartz and feldspar in the border zone of the granite that the suggestion is made that the granite magma furnished those both inside and outside. And then the added suggestion is made that alteration of the schist made it resemble a granitoid groundmass in which the metacrysts resemble phenocrysts (A. L. Anderson, 1934; Schwarz, 1913). This last step has relatively little supporting evidence. There are, to be sure, in the granites,

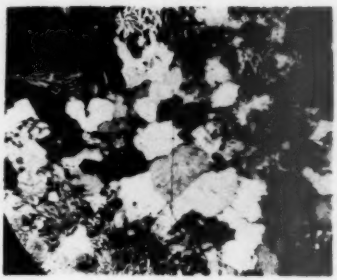

FIGURE 1

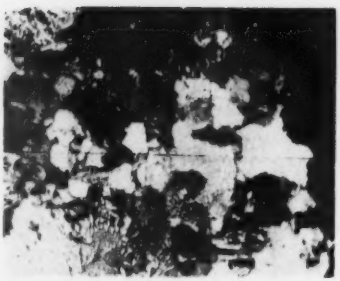

FIGURE 2

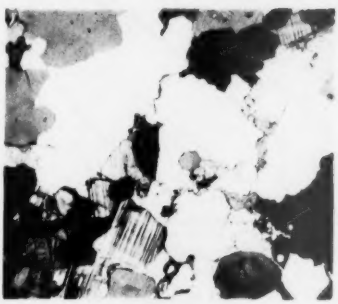

FIGURE 3

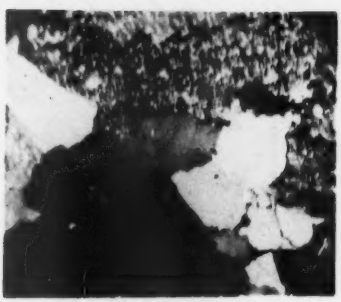

FIGURE 4

FIGURE 5

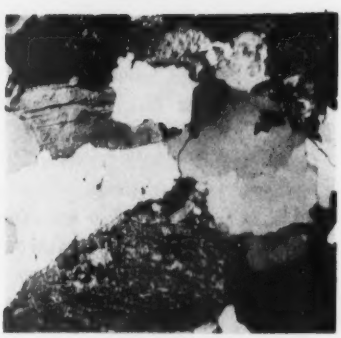

FIGURE 6

QUARTZ MOSAICS IN IGNEOUS ROCKS

Figures 1 and 2, Granite porphyry dikes in granite. x 27. Figure 3, Harney Peak granite. x 12. Figures 4–6, Granites of central Minnesota. x 12.

some residues of schist and some minerals formed by its alteration, but these are more logically attributed to contamination of magma (a well-recognized process) than to an extreme of replacement on such a large scale as has never yet been clearly demonstrated. Hundreds of granites

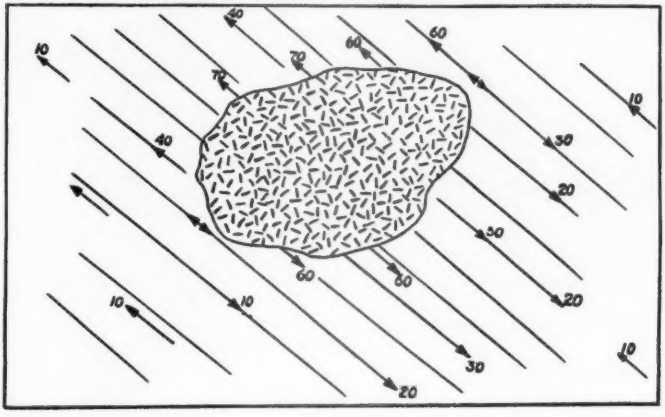

FIGURE 1.—*Sketch of a hypothetical intrusive into steeply tilted beds of uniform strike*

The foliation suggests stoping or replacement, but the pitch of flow lines show displacement in a dome or arch.

have porphyritic facies and many of them are near contacts, but not all are at the borders or related to schists.

Augen in a schist should not ordinarily be interpreted as metacrysts. Normally they have a different origin and history. It is, of course, theoretically possible that a feldspar may grow under pressures so high that an occasional temporary increase in differential stress deforms the part already grown. Perhaps some never really attain a large size by replacement growth without almost simultaneous deformation; but this is not the normal history of augen, which are largely residues of deformation after growth. No example has been carefully described to prove that growth produced augen. Growth by replacement tends to euhedral forms, and later deformation produces augen. Any suggestion that augen indicate replacement should be given very detailed support.

Criterion 6: This is much used in the districts referred to and strongly suggests metasomatic origin. In an igneous-looking mass a series of schistose streaks parallel to the strike and dip of the country rock is enough to convince some geologists that the igneous-looking rock formed

by replacement. Two details should be added before final conclusions are based on such a feature. In the first place dip and strike may be uniform in a district even where linear features show that an intrusive mass has displaced a foliated rock, not replaced it (Balk, 1937, p. 55).

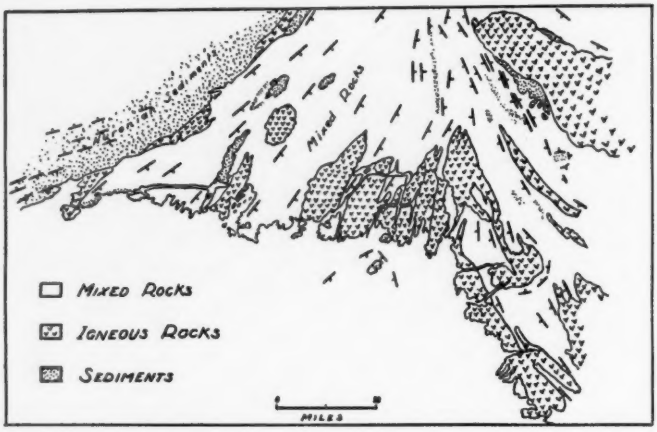

FIGURE 2.—*Structure of the French River area*
Simplified from Quirke (1929, p. 684).

Mapping should be very detailed. In the second place the work of Hans Cloos (1936) and his students indicates that many intrusive masses heat their walls while the magmas cool to partial crystallization and that, in the final stages, the intrusive forces deform the igneous rock and walls together, producing a structural harmony that indicates nothing at all as to replacement. The proof of the displacement may be a structure in the wall rock or it may be a structure in the intrusive itself.

There are also examples in the recent literature where the author claims a uniformity of structure in sediment and igneous-looking rock, whereas his own maps and sections show evidence that the igneous intrusive has spread the layers or beds apart by injection, not replacement (Figs. 2, 3, 4). G. H. Anderson (1937, p. 25, 26) on one page describes bands as contorted and on the next as straight and regular, so that one cannot judge.

The Killarney area has been much discussed, and in the latest paper Quirke (1940, p. 252) makes the structure a basis of strong statements.

"No igneous injection of such size can be supposed to display a vertical structure throughout its mass. It would be a strange coincidence indeed if such an exceptional igneous structure should accord with bedded structure of sediment along and across the strike and in inclusions."

The statements lose all force, however, in the light of many areas recently mapped by the methods of Cloos. It can no longer be considered strange or surprising to find vertical structure in a large intrusive and to find it in harmony with the structure of adjacent older rocks. Writers

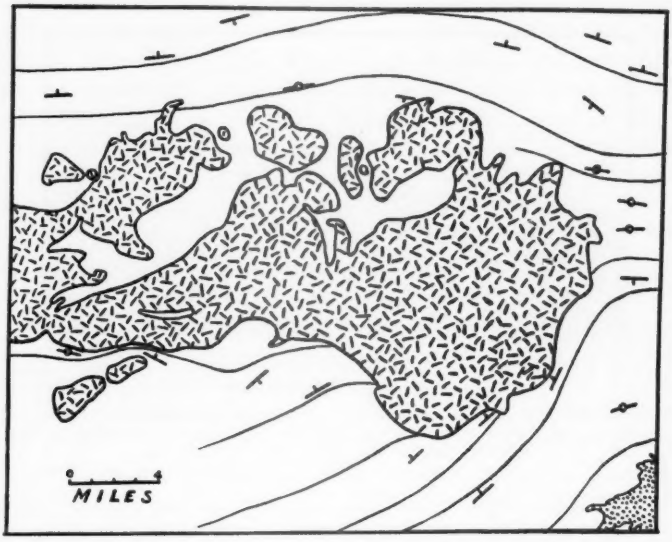

FIGURE 3.—*Structure of an area in Columbia quadrangle, South Carolina*
With strike lines extended to show how largely the intrusive displaced its walls. After Kesler (1936, p. 38).

on granitization should not claim exceptional structures until they are familiar with structures that are common.

In descriptions of Rapakivi granite, experienced men like Sederholm and Backlund disagree in their statements of mappable features, chilled margins, brecciation, apophyses, and contact action.

Criterion 7: The albitization at Sparta (Gilluly, 1933) is an example of a replacement related to a fracture zone; and this clearly noted relation immensely strengthens the suggestion that the albite granite resulted from replacement.

The border position of the Pellisier granite is cited by G. H. Anderson (1937) as evidence that it is a replacement, and the contact position of a rock around the Cassia batholith led A. L. Anderson to believe it was formed by replacement. These are not strong criteria but need much

supporting evidence. Perhaps they are extreme extrapolations of the evidence of replacement in the rims around inclusions in granites. Reynolds (1936) described some quartzite xenoliths at Kiloran Bay, and Holmes (1936) some quartz xenoliths in lavas of Uganda, and both seemed to think the evidences of replacement were so clear in the field that no

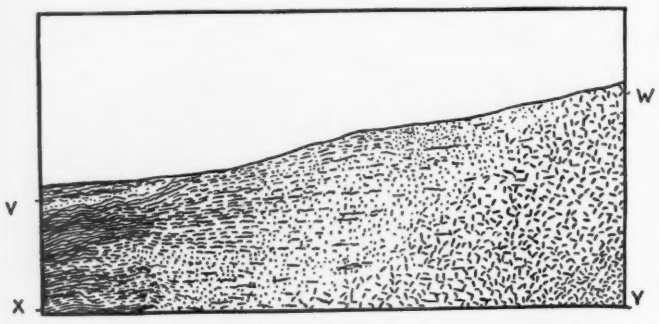

FIGURE 4.—*Diagram of transition from metasediments to intrusive, Inyo Range, California-Nevada*

The lines from x to y diverge from the lines V to W, enough to indicate important deformation by injected magma. Displacement dominates over the possible replacement. After Anderson (1937, p. 34). Said to be typical (p. 33).

more proof was needed. Careful work on similar rims around quartzite fragments in the sill at Pigeon Point (Grout, 1928, p. 573) led to the conclusion that they were products of differentiation of magma rather than replacement of the quartzite. If the proof of the replacement origin of rims is clear, it should be presented and not simply stated. In any case, rims around xenoliths are not much evidence as to the origin of rims a mile or more wide around batholiths.

A suggestion of metasomatic replacement is much strengthened by the occurrence of a near-by igneous mass large enough and of a composition likely enough to supply abundant emanations. Very few such masses have been carefully mapped, however, in support of the suggestion of metasomatism. Backlund (1938c, p. 106) considers the general problem of the space now occupied by granites a strong argument for replacement, but the space may result from stoping or lateral thrusting more often than replacement. Backlund (1938a, p. 380) also cites the lack of visible feeders of sheetlike masses as a sign that they formed by replacement, but, so far as he says, there is a similar lack of channels by which replacing solutions came in, though they should be as easily recognized as the feeders.

To use the lack of some feature as evidence of a process presupposes exhaustive field work on unusually well exposed areas, and such work is seldom indicated in the recent papers though exhaustive work may have been done in parts of the Scandinavian Shield.

Criterion 9: Gradation from an igneous-looking rock to another which is evidently not igneous, is the fact most often reported as evidence of origin by replacement. This is not at all conclusive and must be considered only remotely suggestive—perhaps four to six times out of ten rather than nine times out of ten. Gradations may occur by injection even more often than by replacement. The nature of the "gradation," the primary criterion in most claims of metasomatic origin of igneous rocks, is rarely described by the claimant. It is repeatedly stated as if a glance at the field exposures would convince the most skeptical. Nevertheless, at places the evidence seen by a later worker (Jones, 1930) indicates abrupt contacts. Large scale maps, sketches, or photographs are better. Sederholm presented photographs and sketches and then stated his interpretation of them so emphatically that the pictures are hardly allowed to "speak for themselves" as he says.

Near igneous rocks where such gradations occur the country rocks commonly show a schistosity or slaty cleavage that is more conspicuous than bedding. Tracing a single bed from unaltered sediments to igneous-looking rock is seldom possible. When the traced beds merge into cleaved schists they can seldom be followed, and probably several geologists have followed metamorphic structures rather than the original beds; and, if the rocks show different compositions, the differences should be attributed to originally different beds.

Criterion 9a: The disappearance of sediments where granite has transgressed a uniform series of beds suggests to Daly (1933) the replacement of beds by a process of magmatic stoping. The same absence of sediments may suggest to others a metasomatic replacement. The evidences of either process are not clear from the simple absence of the beds in exposures. To decide whether one of these processes, or both, or neither, has been active needs further evidence, perhaps more detailed mapping (Fig. 1) or the use of other criteria.

Many districts show evidences of displacement in addition to possible replacement (Kesler, 1936; Buddington, 1939, p. 163). It is to be expected that a magma which displaces its walls at one place and at one time may at another time and place give off emanations that alter the walls so that they look igneous.

Criterion 9c: The nebulitic or ghostlike inclusions in granites certainly suggest that the composition has been changed. Where the form is still rather sharply outlined the original form and size have probably been preserved and the difference in composition is conclusive evidence of metasomatism. It is not wholly clear how the magma and inclusion react, however, and it is possible that a black inclusion a few inches across may be "strewed" in a magma to make a larger dark contaminated area of fairly definite outline. The mixing might be mostly mechanical, though metasomatism probably accompanies such mixing at many places.

Criterion 10: The rounded contacts, as distinct from scalloped contacts, are valuable features in the study of replacement ore deposits but may not be fully applicable to igneous contacts with schist. Fahlquist and Berkey (1935, p. 23) refer to embayed contacts as one of the two good evidences of replacement. Embayed contacts may develop in magmas by a corrosion which should not be classed as metasomatism. The embayment may be along a major contact of an intrusive, or in single crystals, or in rock fragments of intermediate size. Corroded quartz phenocrysts in a porphyry now have mineral grains in the embayments, but their growth was not "practically simultaneous" with the corrosion. The "antennae-like processes of feldspar in quartz" noted by Reynolds (1936, p. 383) might be growths from magma long after the magma attacked the quartz. Such embayments are not to be classified as metasomatic.

Criterion 12: The suggestion has been made that replacement of a sediment is commonly accompanied by a filling of a large percentage of pore space. Any recrystallization of porous shale to biotite, accompanied as it is by a considerable loss of water, might leave room for 20 to 30 per cent of introduced material. If this consisted of magmatic emanations of alkalies and silica it might make the shale much more like granite than recrystallization without the filling of original pores. The data are too incomplete to determine whether the suggestion has any value because nearly all shales are recrystallized to slates or hornfelses, and much porosity is eliminated, long before the igneous emanations add much feldspar.

Criterion 13: Helicitic structures have rarely been cited as proof of metasomatism in an igneous-looking rock (Grout, 1937, p. 1566 and Pl. 13) but should be expected almost every time a schist is the original country rock. In contrast to helicitic structures some large crystals are zoned as if by growth in a magma or in open spaces. Zoned crystals are not common though perhaps possible as results of metasomatism.

Anderson (1937, p. 63 and Pl. 9) described zones as "associated with replacement," but they oppose the other criteria of metasomatic origin of those minerals.

Criterion 19: This may be extended to include a variety of evidences of deuteric action in igneous rocks. The replacements may be called metasomatic although the liquid involved is a rest-magma. It is this sort of replacement evidence which "is found in most pegmatites and nearly all granites" (Osborne, 1938). It is very misleading, however, to cite such evidence to support the idea of making a schist look like a granite. Replacement by deuteric action simply changes an igneous rock to a different-looking igneous rock. Furthermore, the metasomatism in deuteric action starts with hot crystals suspended in residual magma, whereas a schist before metamorphism was a cool rock and was compacted by the metamorphism so that it would naturally be very resistant to the action of igneous emanations, even at depths where heat is normal. (*See above,* definition of deuteric.)

Criterion 21: Chemical analyses should be made and used with a clear understanding of probable errors. Calculations based on poor data can never give dependable results (Grout, 1926, p. 518-519). Careless or incomplete work by the analyst should never be used for important calculations.

It is proper enough to add analyses to a description or discussion without any attempt to use them to prove a point. They embellish the paper, and the data may prove useful in other connections; but no one should be misled into thinking analyses are evidences of replacement when they simply show that two rocks are different. Analyses do not show processes. Rocks that differ in analysis may have been originally different or may have become different by differentiation (igneous or metamorphic), by assimilation, by addition of magma, and by various other processes.

Analyses are used commonly in the argument for replacement, as a basis for comment on whether or not the rock resembles some standard rock variety. These comments need the check of a calculation, even though it may be a simple one. Spencer (1938, p. 113) says that the analysis of a certain xenolith is like that of a granite, but a calculation of the norm indicates 5.61 per cent corundum, a proportion found in the norms of very few granites. The analysis that looks conspicuously poor in several constituents to Quirke (1930, p. 89) is normal to Jones (1930, p. 59).

Even those analyses used for calculations have to be supplemented by other data, and the calculations involve assumptions that need dis-

cussion and justification. The necessary data include specific gravity and porosity or apparent specific gravity; but few of the published discussions even mention porosity. If the rocks involved have such low porosity that it is negligible the evidence should be clearly stated. The common remark that rocks have "gained" or "lost" some constituent (Horwood, 1936, p. 102-106), or that constituents had been added or removed (Goodspeed and Coombs, 1937, p. 23), or that there was an increase or decrease of some element (G. H. Anderson, 1937, p. 55-56; Goodspeed, 1937, p. 761) because simple inspection shows different analyses for original and altered rocks, is liable to serious error. Some (Horwood, 1936, p. 109) even contradict themselves.

Calculations based on analyses usually involve an assumption that some constituent has remained constant or that the volume of the rock has remained constant. This may be quite proper in some districts but, whatever the assumption, it should be carefully explained and justified. There may be good reason to assume a certain constancy in one district without making it at all likely that similar constancy can be assumed in another district. If no constancy is indicated, the calculations are of little value unless extended to cover a long series of possible assumptions.

The methods of calculation have been outlined and illustrated very well by Leith and Mead, and by Lindgren (Kemp, 1940). Nevertheless, some recent writers on granitization have not taken the trouble to learn correct methods or to explain how the incorrect methods could give dependable conclusions. Postel (1940, p. 131) claims a potash enrichment without any chemical work at all, and his reported mineral compositions render the claim questionable. Horwood (1936) has no chemical data at all but calculates from an optical measurement. G. H. Anderson (1937) attempts to calculate changes in other constituents on the assumption that alumina maintained a constant percentage in the changing rock—a most surprising idea, because most students assume that in weathering there may be a nearly constant amount of alumina in a certain volume of rock. Waters (1938, p. 783) used a graphic method which he frankly says is a rough approximation. Backlund (1938a, p. 384) uses an old method, "relative to 100% silica," but reports no data on porosity or specific gravity. Nockolds (1935-1937) called attention to this need of data and to the errors of calculation, and recommended accurate methods.

The method of estimating the original composition of a sedimentary formation is not well standardized. Few of the original rocks, supposedly made into igneous-looking rocks by metasomatism, have been

sampled except by the selection of an average-looking hand specimen. It is rarely possible to trace a single sedimentary bed to a point where metasomatism has made it look igneous and be sure that it was originally uniform. Perhaps the best estimate of original composition is made by averaging a group of analyses of the little altered rock and another group of analyses of the altered rock. If the many samples are not very divergent the average may be very satisfactory but, if there are great differences among random samples, even the average is not a safe basis for determining the original nature of rocks that are now altered. No important conclusions should be based on one or two tests of a highly variable formation. The formation, however, may be more constant than the single beds, and the range of its variability is its most significant characteristic.

G. H. Anderson (1937, p. 41-49) has analyses to show that the sediments in the Inyo Range are not all uniform but uses one analysis to argue that the sediment may not be very different from a granite in composition and other analyses to show what "increased" and "decreased" during the granitization and the changes resulting from magmatic emanation. Even his argument that the change from phyllite to granite composition may be slight is based on too superficial a study, for the phyllite has 12 per cent corundum in the norm and is therefore not much like a granite. Miller (1938), in discussion of Anderson's work, notes that a similar rock seems to develop in the mountains in California farther south, even where the original was very different. Assimilation by the magmas resulted in contaminated granites, as Miller says, and Anderson's argument for metasomatism on a large scale is not well supported.

Two further notes may be of some use in the discussion of analyses. First, the changes found probably do not strongly suggest metasomatism if they are radically different from those resulting from metasomatism in other districts. (*See*, for example, the table of gains and losses in inclusions, Grout, 1937, p. 1546.) Second, a calculation of the assumed gains and losses should be compared with a calculation of a simple admixture of igneous magma to see if injection alone gives as satisfactory an explanation of the altered rocks as does a complex replacement.

Criterion 24: As an igneous mineral, cited in support of granitization in a schist, consider perthite, which Nockolds (1932, p. 443) finds in phenocrysts in a dolerite and in similar state in near-by granite. Since the material already in the dolerite might recrystallize to form perthite, its presence is not a clear sign of replacement of the dolerite by emanations from the granite.

OTHER FIELD AND LABORATORY SPECIFICATIONS

The field data should include detailed maps of the areas of (1) normal igneous rocks, (2) the least altered of the country rocks, (3) the igneous-looking rock that is supposed to be a result of metasomatism. Beside showing the areas, maps should show the structure; dip, strike, and the trend and angle of pitch of the linear features—needles and axes of folds—give a basis for interpretation of a third dimension. This may never be wholly satisfactory because large masses can rarely be well known for any great depth below the present surface. The estimates of depths of transition from acidic to basic rocks, however, set some limits on the probable volume of granitic magma in an area (seismologic data indicate depths of 20 to 50 kilometers).

Any evidence in the surrounding region that the masses concerned have been at great depth may be worth adding because at such depths the general heat would promote chemical reaction. Backlund (1938, p. 106) remarks that granitization is not really restricted "to remote depths," but the fact that he remarks upon it implies that it is more to be expected at remote depths.

Another significant field fact is the form of the mass believed to result from metasomatism. The well-established examples of metasomatism are those with evidences of each access of fluids. "Deuteric metasomatism" results from fluid magmas, and other metasomatism is related to fractures or openings along which hot fluids can reach the solid minerals. At high temperatures it is recognized that gaseous emanations may penetrate subcapillary openings and replace a contact zone many feet wide. Nevertheless, no contact zone extensively replaced by igneous emanations has been shown to have a volume of the same order of magnitude as the batholith or stock from which the replacing fluids came. The garnet contact zones are relatively narrow and, outside that zone, the metasomatism is more closely related to fractures.

The form of the igneous-looking rocks supposedly resulting from metasomatism is said to be a zone or rim around some other rock in several districts (A. L. Anderson, 1934; G. H. Anderson, 1937) and said to be related to a shear zone in some. The albitization at Sparta (Gilluly, 1933), for example, is notably related to a shear zone in the igneous rock and, if similar albitization appears in a schist roof rock, it would almost certainly be confined to a narrower zone. The metasomatic replacement of the hood of a large igneous mass by late emanations from deeper parts of the same magma chamber is likely to be extensive because the magma hood, even when crystallized in large part, is still very hot. The roof rocks may also be metasomatically replaced, but this replace-

ment would probably be less extensive because they would not be quite so hot as the magma below, from which they received their heat.

Petrographic and chemical data are reported in nearly every discussion of the formation of igneous-looking rocks from other rocks, and some such features have been listed in the criteria of metasomatism and discussed under the head of Applicability of Criteria. They are the basis of much disagreement.

Probably the most important data in discussions of the metasomatism that is supposed to form igneous-looking rocks are those on the size of the mass. Recent papers show that generalizations and vague suggestions are the rule, and actual dimensions are rarely given. An actual count of the papers where the masses concerned are small (xenoliths, dikes, narrow contact zones, or masses a few feet across) shows 28 occurrences reported. For larger areas the suggestion of metasomatism has been made in perhaps 20 papers, but the quality of the evidence is in inverse ratio to the size. In most of these the metasomatism is seen in a small transition zone, and on the strength of that transition the suggestion is carried on to the larger igneous-looking masses.

There is no proof as yet that such an extrapolation is justified. Probably there can be little doubt in the mind of any geologist with moderate experience with intrusive igneous rocks that some xenoliths of sediments or metamorphic rocks are made to look igneous by reaction and additions. Grout (1937, p. 1539-1549) has compiled a list of examples with references. None of the xenoliths is large, but actual dimensions are rarely stated. Ten-foot blocks may be admitted in exceptional cases, but where are larger ones reported? At several places xenoliths have igneous-looking rims or zones 1 to 3 inches thick, and these strongly indicate that such processes as made them were not extensive.

Nevertheless, the suggestions of immensely greater volumes are common. Spencer (1938, p. 115) says of diffusion into a solid, "the same process . . . if continued longer (or hotter) might produce holocrystalline granitoid structure." This gives no heed to the probability that the process will not continue, but many writers have called attention to the fact that reaction will commonly bring a solid rock and a fluid into an equilibrium, after which reaction ceases; continued metasomatism requires continued passage of the fluid in an "open system." Winchell (1893) says that, if it is true in one instance that a granite originates this way, it is indicative of a law for the generation of all granites. Sederholm (1934, p. 248) says that, if conditions are favorable to the formation of granite magma in small quantity, they may as well have caused the formation of larger quantities. Quirke (1927) described microscopic evidences of replacement and gives them a "regional" (p. 119

and 756) application. Perrin and Roubault (1938, p. 671) say it does not appear absurd to think it happened also on a large scale. Reynolds (1938, p. 75) describes narrow rims and applies the idea to a whole suite of dikes. A paper by Van Bemmelen says "why not go one step farther and suppose that the quartz of the granite is hydrothermal?"

The answer to all these is that there are many reasons. If a man carefully studies an ant-hill and discovers how it was formed, there is no reason at all to claim or suggest that a mountain was formed that way. The better procedure is to make a little series of calculations based on reasonable assumptions.

CALCULATIONS AND ASSUMPTIONS

It is well to try the assumption, first, that the magma itself replaces the older rock and find what became of the replaced rock or how much the magma would be locally modified by the assimilation of the replaced material. See if the calculated materials match those in the field. Compare such a calculated product of metasomatism with a simple mixture of magma (or its igneous rock product) with the country rock, to see if the field facts can be explained as well or better by assimilation or migmatite formation.

It is important to note that in replacement by a magma there is no such method of disposal of the replaced rock as when the hydrothermal solutions carry the replaced rock away to form veins at a distance or to dissipate the material at hot springs. The material replaced by magma cannot be destroyed, and a magma cannot ordinarily carry it far away; it remains as a contamination. We are inclined to think loosely here because water solutions may replace a rock completely and carry away the material; a magma does not. Miller (1938, p. 433-438) gives this problem more adequate consideration than others.

Assume as a second basis for calculation that an emanation from a body of igneous rock (or magma), such as is known or reasonably postulated in the district, has caused the metasomatism. The batholiths mapped are the best basis for this assumption and may be supposed to widen downward for some miles unless the structures observed are opposed. Some plutons, however, are known to grow narrower at depth. In any case a limit must be set to the volume "below," because the batholiths are largely granitic, and at depths the granites and gneisses give way to heavier rocks.

Estimate within rather wide limits the possible volume of emanations to be expected from such a body of magma. Much of the emanation is probably water and, although the water content of magmas is probably very variable, the recent high estimates are by Gilluly (1937).

Even if 10 per cent of the granite magma is volatile, only part of it emanates. To be liberal assume that the whole 10 per cent emanates as water solution and carries about 10 per cent mineral matter in solution; the rock material formed by the emanation is perhaps 1 per cent as large as the batholith. This is an extremely rough estimate but is believed to be of the proper order of magnitude. It agrees well with Vogt's (1931) measurements indicating that about 1 per cent of a granite may develop into pegmatite. Even if no pegmatite was formed and all that mineral matter was available to replace older rocks, the estimate places a valuable limit on the amount of igneous-looking rock that can be formed. It is almost certain to be much smaller than the truly igneous mass from which the emanations came.

To be sure, the emanation which would produce a certain volume of pegmatite might, by acting on another rock, change several times as much rock to a different composition. Most pegmatites, however, are mineralogically close to granites. If one may estimate the composition of emanations as equivalent to the pegmatites produced, they would change a wall rock in about the same way as granite magma. This would seem to be a logical basis for estimating the nature of emanations; but other methods give different results, and the only safe treatment is to try several different ideas as to the nature of emanations.

A second basis for estimating the mineral nature of emanations is by changes in composition during contact action. The changes differ widely in different rocks and as a result of different magmas, but certain trends are very important. The data compiled by Grout (1937, p. 1546 and 1555-1567) indicate that emanations from granite magma may reduce the silica content of some shales (making them less like granite) and increase the silica in others; but the gabbros reduce the silica content of many of their contact rocks and xenoliths. The granite magmas seem to contribute K_2O to many contact rocks, in contrast to the effect of gabbro magmas which leave two-thirds of their contact shales with less K_2O than the original. There are, to be sure, examples of large potash additions by metasomatism (Billings, 1938, K_2O content raised 3 per cent; Quirke and Collins, 1930, K_2O content raised from 1.39 to 6.04 per cent); but these are exceptional, and the average change in potash content is slight compared to that in soda (Blyth, 1935). MacGregor (1937, p. 476) finds potash reduced as a "temporary" consequence of granitization. Eskola (1933, p. 20) believes potash metasomatism is probably not effected by water solutions at great depth but more likely by magma itself. Probably for any general type of magma, the emanations may range rather widely. Nevertheless, it is clear that potash and silica contributions are smaller from basic magmas than from granitic magmas;

Von Eckermann (1937, p. 524) reports that the rest solutions of basic magmas are normally sodic. These reports from several compilations constitute a strong argument against the formation of large masses of granite by metasomatism of sediments by emanations from pyroxenite or peridotite, as suggested by Holmes and by Reynolds. Reynolds (1936, p. 395-397) says

> "all constituents" [of a syntectic syenite], "with the exception of SiO_2 and ZrO_2, appear to have been provided almost entirely by the hornblendite magma. . . . Certain constituents, *e.g.* Al_2O_3, K_2O . . . have . . . become concentrated in the . . . syenite."

Holmes (1937, p. 276-277) refers to "ultra basic magmatic materials and associated alkaluminous . . . emanations."

One calculation by Von Eckermann (1937) proved very instructive. If emanations caused the differences in composition which he found, they were hydrous alkalic fluids rich in fluorine and titanium, fluids not corresponding to any known in the Archean of Scandinavia.

A third method of estimating the nature of emanations is by laboratory studies of the volatilization of various elements in steam, but such tests at high temperatures and pressures are so incomplete that there is much room for disagreement (Ingerson and Morey, 1940, p. 778-783). Graton (1940, p. 347) argues that the ore-forming emanations are liquid, and the solubility of several compounds in hot waters is not so uncertain as that in steam.

The compilation of results cited shows so much variety that there are clearly other factors involved beside the nature of the magma. Several geologists have noted an apparent "selective precipitation" exerted by different wall rocks, which is astonishing. Fenner (1938, p. 1471-1472) finds rhyolite probably causing some replacement of basalt with maintenance of a surprisingly linear relation, but no sign in rhyolite veins of contamination by basalt. Backlund (1938, p. 107) notes that the granitization matter varied with the material undergoing granitization. Grout (1933, p. 210) found that the supposed aqueo-igneous effects in Minnesota, to produce different igneous rocks, required very different emanations or contributions from a deep-seated magma source; one sandy shale was supposedly turned to granite, and another of similar original character to gabbro.

It certainly is surprising at first thought to read the suggestion that emanations from a particular granite magma (emanations clearly different from the magma left behind) turn rocks of several different kinds into a mass resembling the granite. Substance (A) gives off substance (B), and that turns substances (C) and (D) "regardless of composition" (Graton, 1940, p. 302) to a composition like substance (A). Equally

puzzling is the idea that emanations from basic magmas turn a whole series of rocks to granite. Substance (E) gives off substance (F), which turns rocks of compositions (G) and (H) into a composition like none of the four but like a new substance (K). Such astonishing suggestions carry a heavy burden of proof. Nevertheless, the suggestions are made (MacGregor and Wilson, 1939, p. 208), and the results are credited to "selective replacement." The proof of its reality, however, is not complete, and the idea of replacement is over-extended when emanations are credited with an effect that is more simply explained by injection and assimilation. As stated by Von Eckermann (1938, p. 114) different sediments have to order by special delivery their own transmuting emanations, and (1937, p. 520) it seems that, if the emanations are responsible for rapakivi granite, different emanations were restricted to different levels in the sediment. MacGregor and Wilson (1939, p. 208), however, think the rocks themselves select the emanations they need from a long list sent around "on approval." Eskola (Barth, Correns, and Eskola, 1939, p. 378) refers to metasomatism as "selbst vermittelt." Is it possible for two shales of the same composition like those in Minnesota to select from the emanations sent "on approval" so differently that one becomes a granite and the other a gabbro?

In the absence of a calculation on the possible volume of emanations some writers have suggested surprisingly large volumes of granite as a result of emanations. Fahlquist and Berkey (1935, p. 25) suggest that the granite which was formed from magma itself and that from emanations are "equally large." Guimaraes (1938, p. 90) concludes that "all the granites" of Brazil result from magmatic emanation, but one looks in vain for any report of a large igneous rock, the magma of which could have given off the great volume of necessary emanations. A. L. Anderson (1934, p. 376) estimates that the area (volume not closely estimated) of the Cassia batholith is three times as great as it would have been if the wall rocks had not been replaced.

A final suggestion as to the nature and source of the fluids active in metasomatism abandons the field evidence that metasomatism is related to intrusive rocks (Moore, 1940, p. 127). This last suggestion attributes them to emanations "from the depths" (Wegmann, 1935, p. 345-346). It is not a new suggestion but has long been kept in the background because of the strong evidences of local sources for the emanations. Butler (1941, p. 59) gives the idea an impartial presentation, with references to papers by those who favor it, and the wise remark that a "field still exists for fact gathering," in spite of the constantly growing record of facts that relate the ore bodies and metasomatism to igneous

magmas and the igneous rocks closely associated in the field. As Moore says

"the consensus is overwhelming that the . . . deposits may properly be tied to magmas of certain ages and to certain igneous rocks derived from them."

STATE OF THE REPLACING FLUID

The fluid bringing about the supposed metasomatism producing igneous-looking rocks may be (1) a gaseous emanation, (2) a hot water (hydrothermal) solution emanation, (a) concentrated or (b) dilute, (3) a residual magma (not always distinguishable from 2a), or (4) the magma itself at an earlier stage of evolution. A question arises as to the capacity of these several fluids to do the work. Viscosity is high in some magmas, and concentration may be low in the dilute water solutions and gases at low pressures. Some of these points have already been noted. Geologists disagree widely as to the probable nature of the fluids, and it is possible that two or more kinds of fluids act in succession.

Fenner (1933) suggests that emanations may replace part of the rock but that possibly at a later time the emanations are followed by actual magma causing further metasomatism.

Nockolds (1933) divides the attack of a magma on an earlier rock into two stages—first a reaction, and second an injection and mixing. His evidence that the two are successive rather than simultaneous, however, is not so strong as the evidence that some rocks have been affected only by the first process. It seems likely that, close to the magma, injection and metasomatism both begin at once, but the emanations may penetrate much farther than the small magma dikes of lit-par-lit injection. It certainly is not to be expected that metasomatism ceases when the magma finally comes in contact with the rock that has been preheated by emanations.

Fenner (1938, p. 1548) believes the emanations from rhyolite into basalt in Yellowstone Park were so hot as to be vapors rather than hydrothermal liquids. Freeman (1938, p. 696), Horwood (1936, p. 109-110), and Gilluly (1937, p. 438) believe the solutions involved in metasomatism were "dilute" or "tenuous solutions." Only "thin solutions" are credited with the granitization by Van Bemmelen (1938, p. 10). Freeman (1938, p. 697) and Bastin (1935, p. 733) refer to hydrothermal fluids without very definite indications of temperature. Sederholm (1926, p. 88-89) referred to granitization "ichor" as a rest magma. Eskola (1933, p. 20) concludes that the granite magma itself is the granitizing "ichor"; agreeing in this with Fenner (1933), and with MacGregor (1939, p. 212) as to the fluids active at a late stage in granitization.

MacGregor and Wilson (1939, p. 199) note that Horwood (1936) claims the granitizing emanation was an end stage material from the magma, whereas others seem to prefer early emanation while the magma was still hot. Fenner (1940, p. 886) says the general idea seems to be that granitization is "due to emplacement of some sort of emanation . . . of the magma advancing ahead of the main body and later followed by an invasion of the main fluid magma." Graton (1940, p. 302-303) may have had in mind the same contrast when he referred the ore-forming fluids to late residues because their effects on the wall rocks were different from those of early contact metamorphism. He gives no consideration to the idea that emanations may be continuous from first magma intrusion to final solidification of rest magma. There is little reason for the contrast he draws between early and late. Along the roof and hood of many batholiths, early pegmatites are cut by later ones, and there is compelling evidence that some pegmatites formed very early (Grout, 1918), at least before any great part of the magma crystallized. Wegmann (1938, p. 49) reports several generations of pegmatites.

Graton also confuses the idea of a late magma residue by the suggestion of an immiscible separation of two liquids, one rich in volatiles and the other rich in silicates. The liquid rich in silicates is the residual magma if such a separation ever occurs (Ingerson and Morey, 1940), and the fluid rich in volatiles probably emanates from the magma and should not be called a magma at all.

Horwood (1936, p. 109) concludes (with little evidence and no support in his references) that the granitizing fluid is alkaline. Graton (1940, p. 343) finds it likely that the late magmatic liquids introduce alkalies. Ingerson and Morey (1940, p. 783-785) clearly show that much depends on the composition of the original magma and that the possible acid or alkaline reaction is a problem that must be worked out again for each individual deposit. Fenner (1940 p. 885) notes that an alkali-rich fluid is not necessarily alkaline in reaction and retains his ideas of acidic gaseous emanations, followed at some places by late magma advance.

DISCUSSION OF DATA

Granting the common occurrence of evidences of metasomatism in the igneous mass and in the country rock, it is well in the next place to compare the importance of metasomatism with that of other processes which might produce the igneous or igneous-looking rock with all its peculiarities.

First there is needed a frank discussion of the evidences that magma may have displaced the wall rocks in larger volumes than it replaced them. Where the structure planes "fan out" as in many districts (Quirke,

1929, Fig. 1; Stark, 1935, Fig. 7; G. H. Anderson, 1937, Fig. 4) or bend out around an igneous mass (Kesler, 1936; Buddington, 1939, p. 163) as in the classic examples in the Black Hills, Bidwell Bar, and Rainy Lake, the argument that the igneous-looking rock made space for itself by metasomatism has no force at all—the space was obtained by crowding the walls aside. Even the presence of augen indicates a deformation that makes it likely that the wall rocks were pushed aside by magma. Thrust faults in the country rock may indicate similar deforming forces making room for magma near the surface.

The traces of sedimentary or metamorphic structures in igneous-looking rocks may be explained in more ways than one. If the rock was made igneous-looking by metasomatism they are relics that escaped the most intense replacement. The same structures may appear, however, in a truly igneous rock as a result of inclusion of a small number of fragments of the wall and their partial assimilation (contaminating the magma) and strew. The criterion most often cited against the idea of inclusion and strew is the orientation of platy structures—the parallelism of foliation inside and outside the igneous-looking rock. It must be recognized, however, that this is not at all conclusive. A high proportion of magmas intruding schists heat their walls so that, by the time the magma is largely crystalline, the schist may be heated to a temperature of easy flowage, and any intrusive forces will act on both rocks, deforming them together and producing structural harmony. This is no sign of origin by replacement, although the action is no doubt accompanied by reaction between the magma and its wall or fragments of wall. Metasomatism may be freely acknowledged in both rocks without any suggestion that the main body was made igneous-looking by the metasomatism. Long ago Emerson (1899) described a granite in which it was possible to map areas once occupied by different schists and recognized assimilation, contamination, strew, and injection. No doubt the rocks show some metasomatism, and his area may be one in which some geologists today would find a good chance to suggest a metasomatic origin. Emerson had a perfectly satisfactory explanation of the features he saw, however, without reference to such an extrapolation of the metasomatism.

A third process to be considered is a continuation of lit-par-lit injection into a schist until the added granitic material dominates so largely that it may be described as granite with residual schist fragments, not necessarily much changed in dip and strike. This might possibly be considered equivalent to the process noted in the last paragraph. There is some difference, however, between deformation after blocks of country rock are included and heated, and injection along early planes of

schistosity in the country rock; but when the injected material dominates so much that the migmatite looks igneous there must necessarily have been some spreading of the foliation planes of schist and therefore some deformation.

Here also there are no doubt some reactions between schist and magma, but the schist in the mixture does not become igneous-looking in the residual stringers even when the granite component is 95 per cent of the migmatite. A clear description and discussion of the process were long ago given by Fenner (1914) and have not been improved by recent suggested modifications.

Finally there may be rocks that become igneous-looking by palingenesis (refusion, anatexis) or possibly by partial refusion to a plastic state often called rheomorphic. So far as the processes produce magma or partial magma the rocks should be considered truly igneous, and the replacement that occurs in the solid remaining unfused is a minor factor in igneous appearance. The importance of such palingenesis in the crust is uncertain, but some rocks may have been softened at such depths as to approach the zones of magma generation. These would be exposed only where erosion is especially great and can be expected only locally and only in the great Shield areas.

METHOD OF PRESENTATION OF RESULTS

With all these processes to consider, the choice of one particular process such as metasomatism to explain a large volume of rock is a matter of balancing the importance of a complex group of criteria. No one who takes the position of an advocate and tries to persuade his readers without evidence and ignores evidence of the other possible processes can claim a good example as the basis of future suggestions. The writer believes that, in most of the granite areas that have been described, the evidence that granite magma displaced its walls is as strong as—in some cases even stronger than—the evidence of replacement. This evidence should not be assumed to be weak just because it is seldom mentioned in geologic reports. It is the evidence easily seen by beginners on their first trips to an igneous district and largely taken for granted as common knowledge thereafter, namely, the apophyses penetrating the wall rocks and the fragments plucked from the wall and included in the magma. There is also the evidence of lava flows of about the same range in composition, which come out from the interior of the earth as liquid and show that some such liquid was once inside and likely to form intrusive rocks.

It should not be necessary to present these elementary data, but some recent writers imply that no evidence is available for an igneous origin

of granite (Van Bemmelen, 1940, p. 30 and 32; Holmes and Harwood, 1937, p. 249). No one should do that.

When the idea of normal igneous origin, with normal reaction on inclusions and with normal differentiation, suffices to explain all the features found, the suggestion of an origin by metasomatism should be held in abeyance until as much evidence is at hand for that process.

When a subject has been discussed as long as this one, it should not be presented as if it were a new idea. When an idea is new, a modest and impartial presentation might not gain the attention that the new idea deserves. It is proper in such a situation to cite all the suggestive evidences, all the analogies, and all the features which should lead to a receptive attitude toward the idea. If the originator of the idea carries it too far or applies it too widely, others may correct him but, if he does not apply it as far as he can, the idea may be ignored.

After long discussion, however, the attitude of a scientist should change to that of a judge, balancing the evidence for and against a process and favoring the one that has the most evidence of a good quality. The careful petrologist presents in full the "orthodox" idea and then, if he likes, calls the attention to other working hypotheses without any extra vigor in advocacy of the "unorthodox" idea. Only a few papers, however, take that attitude toward metasomatism and granitization. Most of them present the idea as if it were new. Keith (1916) describes a "new form of metamorphism" "which may be accessory in forming plutonic rocks." Kesler (1936, p. 32) offers his suggestions as "contributions to our knowledge of intrusive processes," whereas his contribution is a description of a new district, to which he applies an old theory of processes related to intrusion.

Loose statements or phrases are almost as common as loosely defined terms, already discussed. Some fact is said to be "obvious" (Goodspeed, 1937, p. 745; Anderson, 1937, p. 54; Sederholm, 1926, p. 94, 107-108; Goodspeed and Coombs, 1937, p. 23); or "evident" (Collins and Quirke, 1930, p. 383); or "apparent" (Anderson, p. 43, 55, 66); or something "clearly happened" (Agar, 1923, p. 133); or "we are aware" that it happened (Sederholm, 1926, p. 29); or "there is no good reason why not" (Anderson, 1937, p. 19).

Many writers state that there is evidence but do not give the evidence to their readers. Anderson (1934, p. 388) says titanite gives evidence of late deuteric introduction but does not say what feature of the titanite leads to such an interpretation. Stark (1935, p. 14-15) says "a study of many contacts between the two indicates the microcline to be the later" and the quartz is "replaced by perthite and microcline," but the reader does not see the evidence, and Stark's Figure 12 shows an almost

graphic pattern. Schwarz (1913, p. 37) says the Sea Point "granite shows that it originated by replacement," but the description of it does not show that. Keith (1916) says "it appears that they [certain minerals] grew from solutions," but the reader sees no evidence of a solution other than a magma. Schaub (1929) mentions "abundant evidence of replacement of quartz by feldspar" without giving the reader that evidence. Reynolds (1934, p. 596) says "the evidence of the origin of the fused sediment is to be found in the wall of the intrusion," but few of the readers can look carefully at that wall; and elsewhere (1937, p. 258) that "the evidence of replacement is striking," though not saying what the evidence is. Waters (1938, p. 783) says it is "evident that volume changes took place." MacGregor (1938, p. 472-473) says "marginal quartz-diorite shows evidence of its hornfels origin." Freeman (1938, p. 696) says "the evidence points toward introduction by tenuous solutions," and "paragenetic studies show some replaced. . . ." Goodspeed (1939, p. 416) describes dikes which cut the country rock but are cut by the material in their walls, which is "evidence that many dikes are older"; though the reader sees only two conflicting criteria. He adds (p. 418-419) that "their mineral assemblages suggest that they are hydrothermal solutions," and that "contact relations . . . suggest replacement," but gives the reader little data as to mineral assemblages or contact relations. Van Bemmelen (1940, p. 31) says that "the presence of miarolitic cavities is an indication of the depth of formation," but we do not all agree as to the method, to say nothing of the depth, of formation of such cavities. Goodspeed and others (1941, p. 198) say "thin sections . . . indicate . . . replacements" but they do not tell what features indicate it.

Statements are commonly made as if the geologist were an eye witness of the process of formation of the rocks. Goodspeed and Coombs (1937, p. 19) say that under the microscope the rocks "are seen to be of clastic origin." Quirke (1929, p. 698) says the "streaks that look igneous . . . did not move." Osborne (1930, p. 77) says "no movement took place during the formation of the gneiss." Anderson (1934, p. 390) says "emanations permeated the granitic core itself" though he does not suggest from what they emanated. Reynolds (1936, p. 383) says feldspathization "can be seen to take place." Kesler (1936) says "the strike and dip remained the same" during a granitic invasion, and that "replacement progresses rapidly." The "mode of origin of porphyritic rocks has been observed" by Van Bemmelen (1940, p. 27), who adds that one of the rocks "can be seen as a fixed stage in the process of granitization." Perhaps Van Bemmelen's most extreme remark is that (1940, p. 24) the theories of metasomatic recrystallization "are based on exact observa-

tions" contrasting them with theories of differentiation as if he had seen the process of replacement and no one had any more than "a complex of hypotheses" to support differentiation.

A similarly questionable mode of expression is the denial of some occurrence or possible evidence as if the geologist who did the work had seen every particle of evidence that could ever be discovered. Holmes and Harwood (1937, p. 251-252) say of emanations "there can be no evidence for Bowen's statement that they originated . . . as a residual fluid." Goodspeed (1937, p. 760) says "there is no suggestion that they were formed from a true melt." Other geologists might find evidence, so that such denials are of little weight, unless accompanied by a fairly detailed statement as to what was sought, and how, and where.

On the other hand the more generally recognized processes are referred to as based on "no evidence" (G. H. Anderson, 1937, p. 35; Stark, 1935, p. 24-25); or "unnecessarily complicated;" or they are "strange indeed" (Quirke, 1940, p. 252). (*See also* the remarks above about structures of replacement and displacement.) MacGregor (1937, p. 477) says "it is more reasonable to postulate an origin by a process for which there is evidence than to accept . . . magma the origin of which is completely unknown;" but in its context this implies that quartz diorite magma and its intrusion and differentiation are things which are completely unknown. No one should suggest that.

A lack of logic also appears in several papers. No observations known to Van Bemmelen (1938, p. 10) directly oppose the origin of certain rocks by progressive metamorphism, and he concludes "it seems therefore more probable that the rising solutions . . . caused a progressive metamorphism and finally . . . granitization;" more probable than a "juvenile granitic melt." Is a thing more probable because it cannot be disproved? Again (1940, p. 28) he finds dark inclusions are more likely xenoliths than segregations (quoting Grout, 1937), after which he concludes that they are metamorphosed solids (without any consideration of the idea that they might be fragments of igneous walls) and that they are "objections against the molten-state theory." In a group of conflicting hypotheses, the most probable is the one with the most criteria in its favor and the smallest number against it. G. H. Anderson (1937, p. 9) reports "xenoliths" abundant in a rock which he says is granitized schist. A schist remnant in a largely granitized schist is certainly not "foreign" to the formation, and hence not a xenolith. Probably he used the wrong term; but, if the xenoliths are there, they refute his argument that the granite is metasomatized schist. Gallagher (1937, p. 50) quotes a statement to the general effect that segregations represent early products of crystallization— a statement open to discussion—and then concludes that

"obviously the process of metasomatism is foreign to magmatic segregation." Even if the first statement were always true, his conclusion does not follow, because it is well known that early minerals react with late magma residues. Waters (1938, p. 764, 775, 778) describes hornblendic inclusions which are first feldspathized and which later lost their feldspar allowing the "hornblende to pack together." This reversal of the action is not explained except to say that there was a liquefaction of the felsic constituents to permit the second action, and of course that explains nothing because feldspathization must have involved a fluid. It is especially difficult to believe because he has noted (p. 775) that the magma has been contaminated by mechanical incorporation of part of the xenoliths—the "strew" described by many petrographers. Why is some hornblende strewed while the rest is packed together?

It is true that the criteria of geologic processes may be conflicting, and this may explain some statements in the published papers which seem to contradict others (Osborne, 1930a, p. 77, 80; Horwood, 1936, p. 109; MacGregor, 1937, p. 471, 474-475). Nevertheless, although conclusions are not always certain, one cannot reasonably argue from the uncertainty that the unlikely process should be emphasized (Reynolds, 1936, p. 404). When the evidences have been balanced, the idea that has been proved to apply in certain districts should be favored until the other idea has been proved to apply in at least one district.

A final criticism of the method of presentation of papers on replacement is based on the writer's experience in following up references given by the authors of papers on granitization and metasomatic processes. Several who write as if some other man had evidence or data to support an opinion or conclusion mislead the reader, because the author cited gives no such evidence or data.

Arguing that the granitizing solutions are alkaline, Horwood (1936, p. 109) gives nine references; six of the papers seem to favor acid solutions, and the rest leave the matter in doubt. He also refers to the state and concentration of the emanations at different depths and pressures, citing a paper by Goranson in which there seem to be no such conclusions or inferences. Barth (1936, p. 841) refers to Eskola's use of the term anatexis to include emanation effects; but Eskola (1932, p. 473; 1933, p. 17, 20) clearly says "re-fusion" in contrast with Barth's "re-solution"; and adds that Sederholm's "ichors can hardly be conceived as anything but . . . magma"; and above this there are "hydrothermal intrusions chiefly in . . . quartz veins." Reynolds (1935, p. 469, 480-481) says "it is evident from the literature that syntexis of ultrabasic magmas and sediments has taken place" in a district described by Grout (1925 and 1929) but Grout vigorously disagrees. Kleeman (1937, p. 219) says of his

granite, "many of the plagioclase crystals are zoned, a circumstance which Bowen considers a clear proof of contamination"; but no such idea is conveyed by Bowen's book. Biscoe (1940) cites Anderson as holding "that the Cassia batholith as a whole" has been formed by granitization, whereas Anderson suggests two-thirds of the area. Holmes and Harwood (1937, p. 259) cite the rocks of Minnesota-Ontario described by Grout (1925) including a hornblendite that they say is the apparent source of emanations, though Grout gave convincing evidence that it was an early differentiate of granite magma. G. H. Anderson (1937, p. 28) describes a process he calls granitization and then says one man prefers the term "assimilation" for that process; but that man actually disagrees as to the nature of the process, not as to the term.

No doubt some of these errors are read into the original papers by accident, but they are so numerous that they indicate that the writers are avidly searching for evidence on one side of the problem and may not be impartial.

Fenner writes (Personal communication) "it sometimes comes as a surprise to me to find what meaning (or lack of meaning) geologists have attached to views I have published."

CONCLUDING STATEMENT

The present suggestion, then, is that anyone who thinks he has a large mass of igneous-looking rock formed by replacement should not simply give it a superficial glance and make the suggestion, but should give it preliminary study and, if it seems favorable, call for research funds and send for a group of experts in several lines—structure, chemistry, petrology, metamorphism, geomorphology, and so on—to make sure that none of their special abilities serves to throw the idea out of the bounds of possibility. If all agree that the evidence is strongly favorable to the idea, then we shall have at least one good example to which geologists may be referred as evidence that the idea is a good working hypothesis.

To emphasize the suggestion of co-operation it is noteworthy that in two districts where the rocks have been studied by different geologists there is a good deal of disagreement—in Scandinavia and at Killarney, Ontario. There is the conflict between Backlund, Magnusson and Von Eckermann, and that between Quirke and Jones. Reconnaissance is no longer enough.

Several of the papers cited give the reader the feeling that their authors may have good examples of large masses of igneous-looking rock formed by metasomatism but that the presentation of evidence is not convincing. Field and laboratory work should be very complete, and the report should

be worded with accuracy and logic, balancing the evidence rather than selecting the points that favor one interpretation and ignoring others.

Some experienced petrologists find metasomatism of doubtful importance. Eskola (1933) believes the idea of replacement applied to pegmatites "is exaggerated." Loewinson-Lessing (1939) thinks metasomatism makes igneous-looking rocks, but of minor importance, diverging in this respect with Holmes and Reynolds, and still more with Backlund. Moore (1931) says it is "a serious question . . . whether the normal granite of the large batholiths can actually develop in place. The writer is inclined to doubt such an origin."

The formation of igneous-looking rocks by metasomatism is just one part of the very large and complicated process by which igneous rocks are emplaced. There are many partial processes of emplacement—rock flowage and faulting may occur in the wall rocks, and the magma may assimilate and stope its roof as well as give off emanations into its roof. Neither of these processes makes the others unlikely. Careful search should be made for evidences of all such possible processes. If we can show petrologists generally that metasomatism has in any one case made a large mass of rock look igneous, though it had not looked igneous before —if it has happened once, as it very possibly has—then the idea may more safely be suggested to explain masses in which the data are less complete. If the presentation of the description and argument is moderate and philosophical in tone, it may serve a useful purpose in keeping petrologists in a receptive mood toward multiple working hypotheses.

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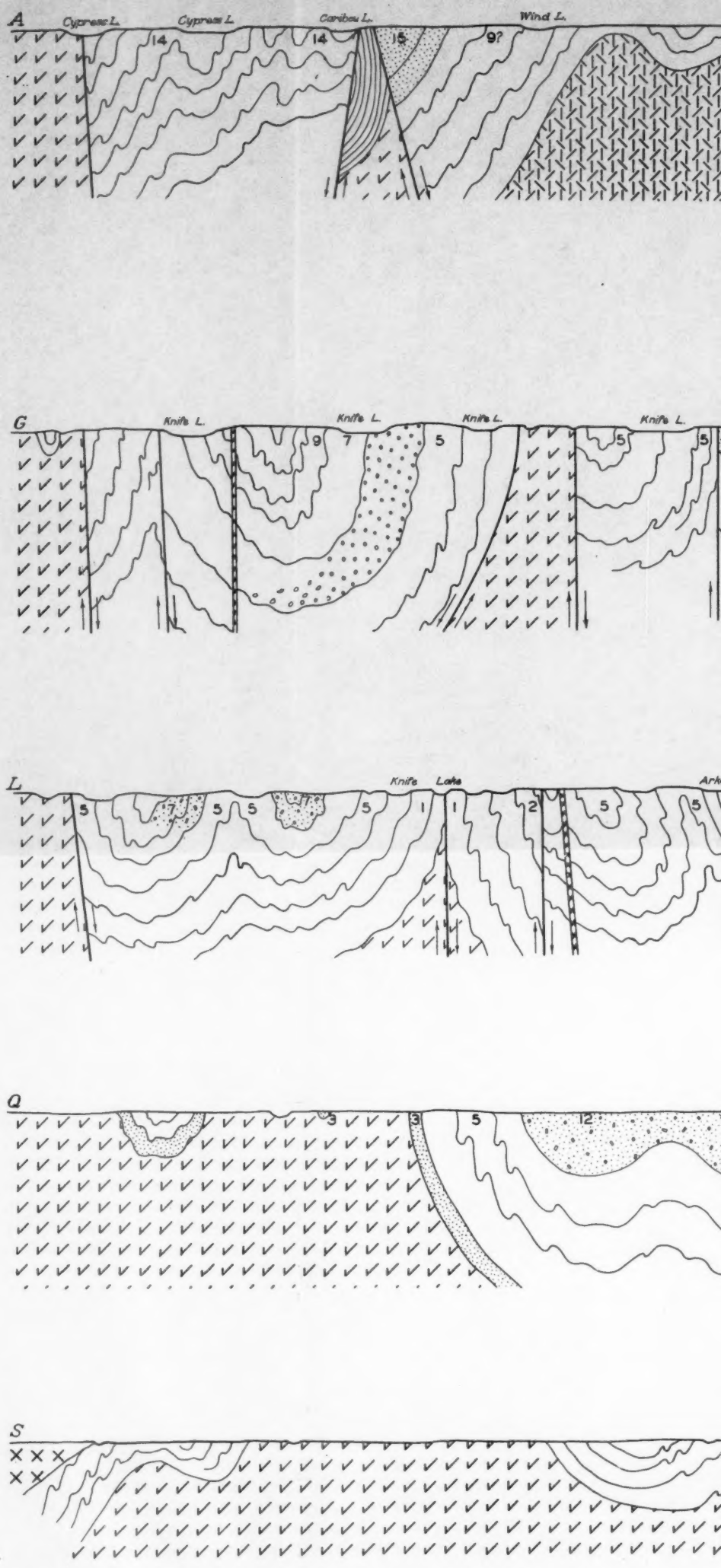
Manuscript Received by the Secretary of the Society, January 9, 1941.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Caribou L.
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B

C Cypress L. Rabbit L. Ester Lake Wayne Lake

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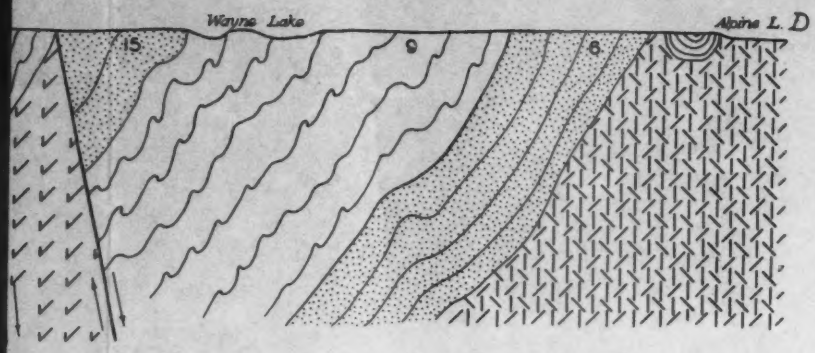
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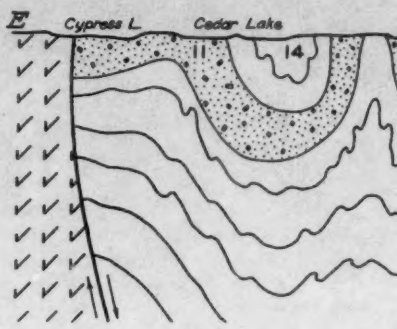
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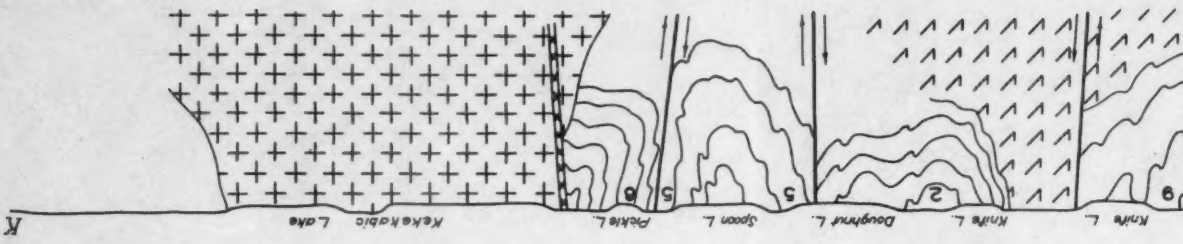
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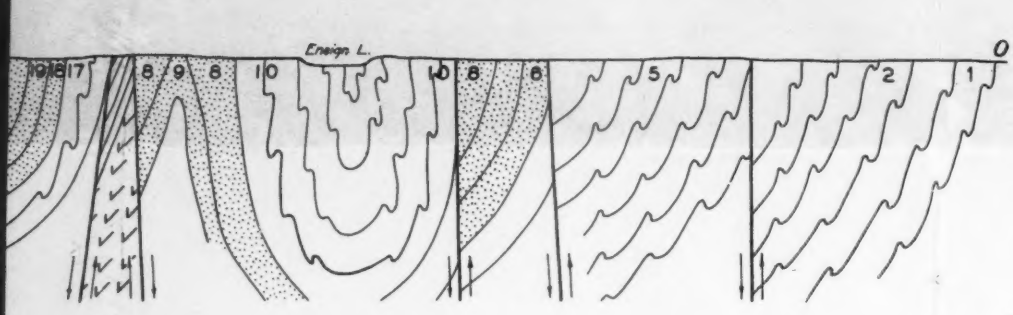
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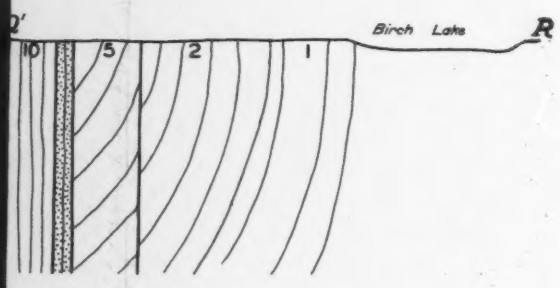
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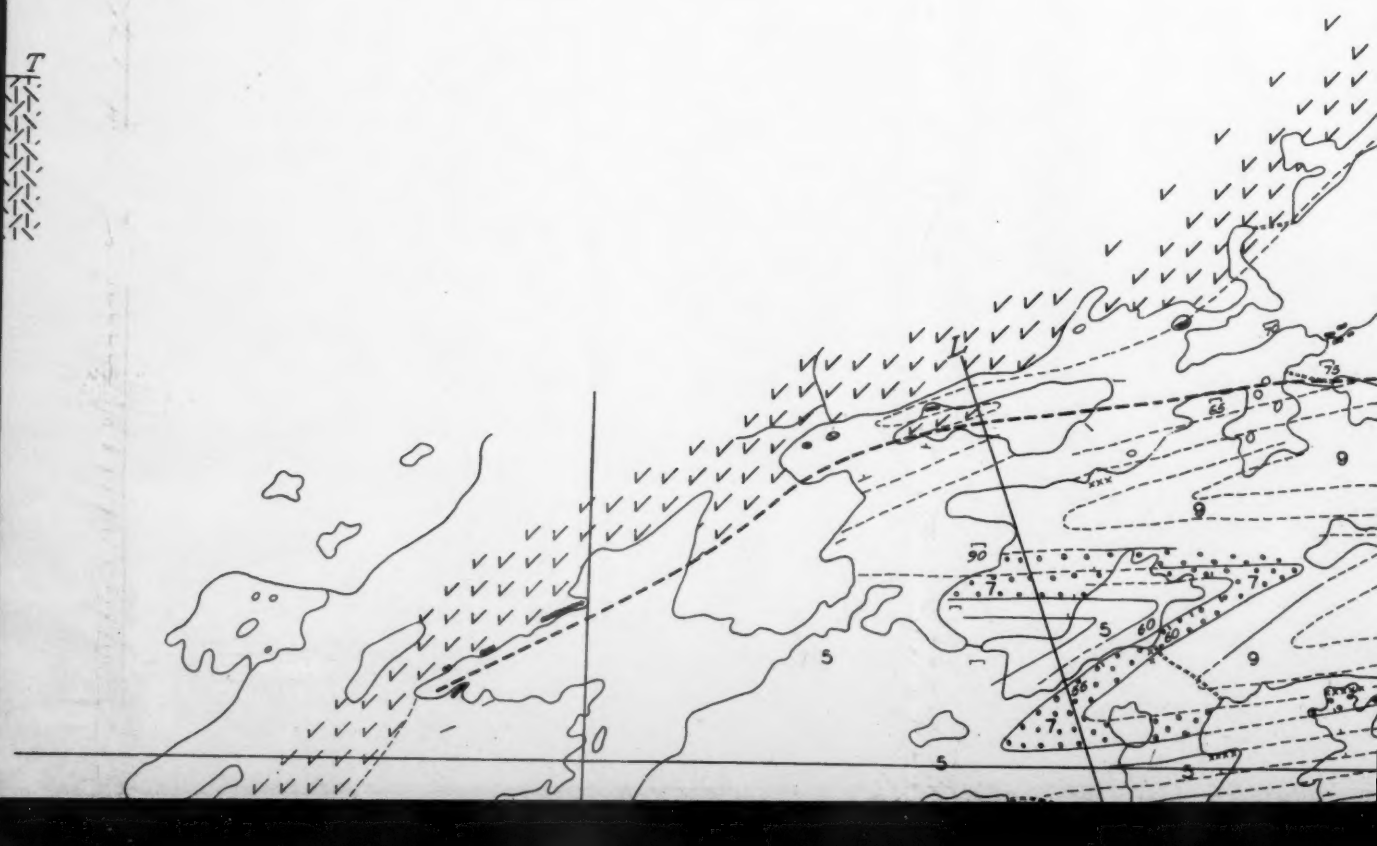
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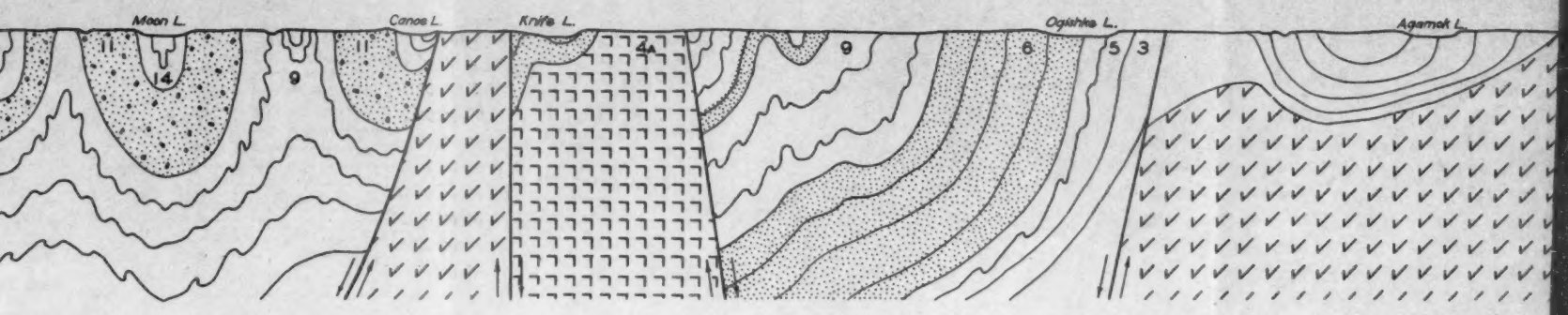
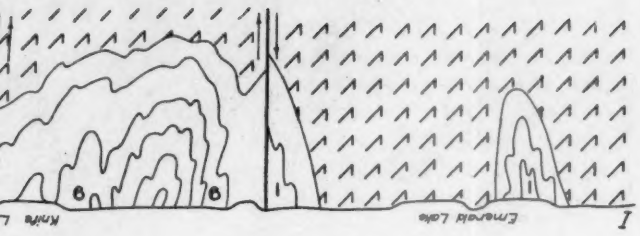
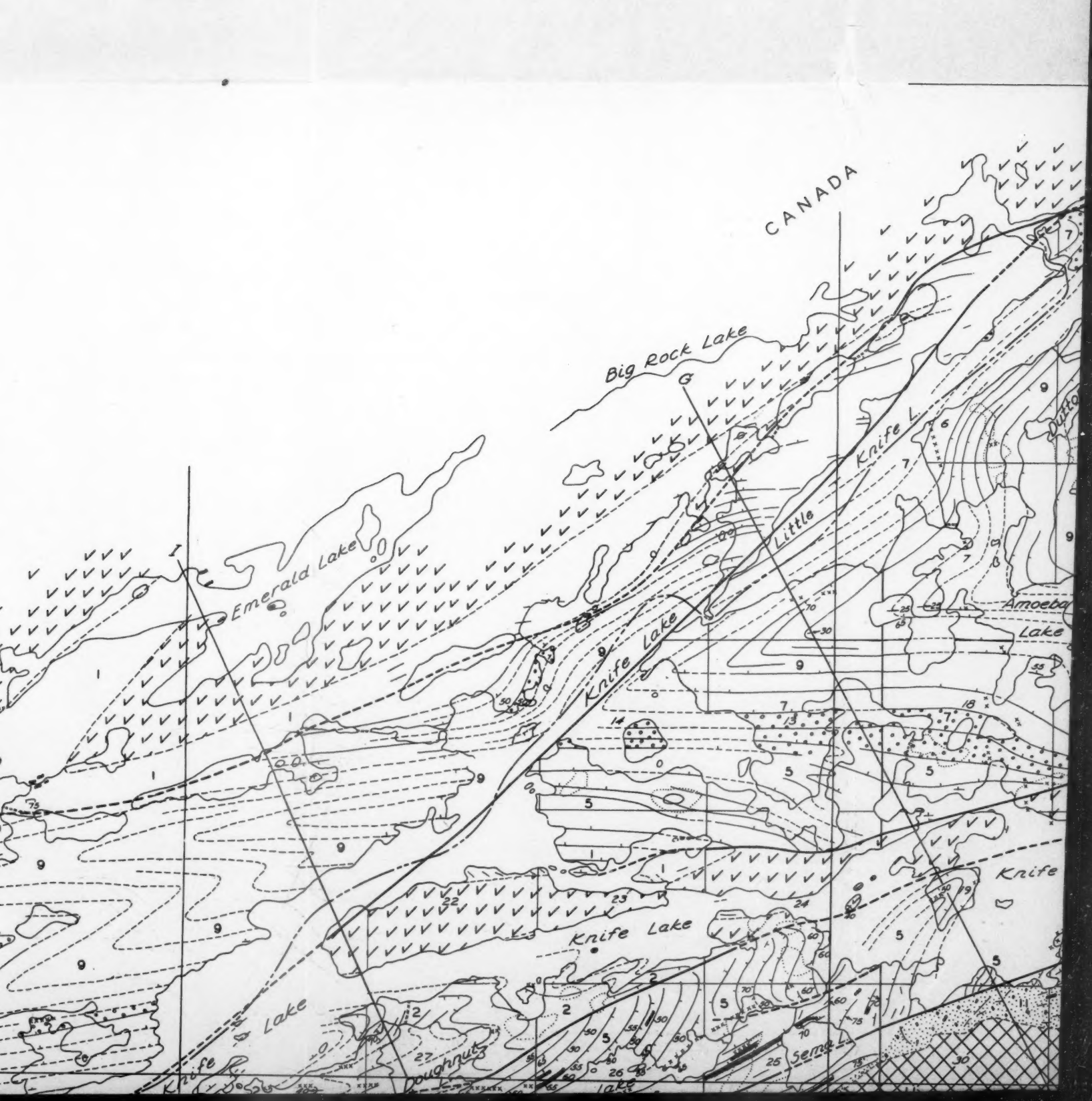

Moon L.
Canoe L.
Knife L.
Ogishkе L.
Agamok L.


Emerald Lake
Knife L.


CANADA
Big Rock Lake
Knife L.
Little
Emerald Lake
Knife Lake
Amoeba
Lake
Knife
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Lake
Knife
Doughnut
Lake
Semo L.

Ogishke L.
Agamok L.
F
5
3

Jasper L.
Cypress L.
Caribou L.
Rabbit L.
Ester L.
Crooked L.
Cedar L.
Gebrard L.
Moon L.
Dutton L.
Knife L.
Little Knife Lake
Cherry Lake
Hangon L.
Canoe L.
Star L.
Amoeba Lake
Knife Lake
Eddy L.
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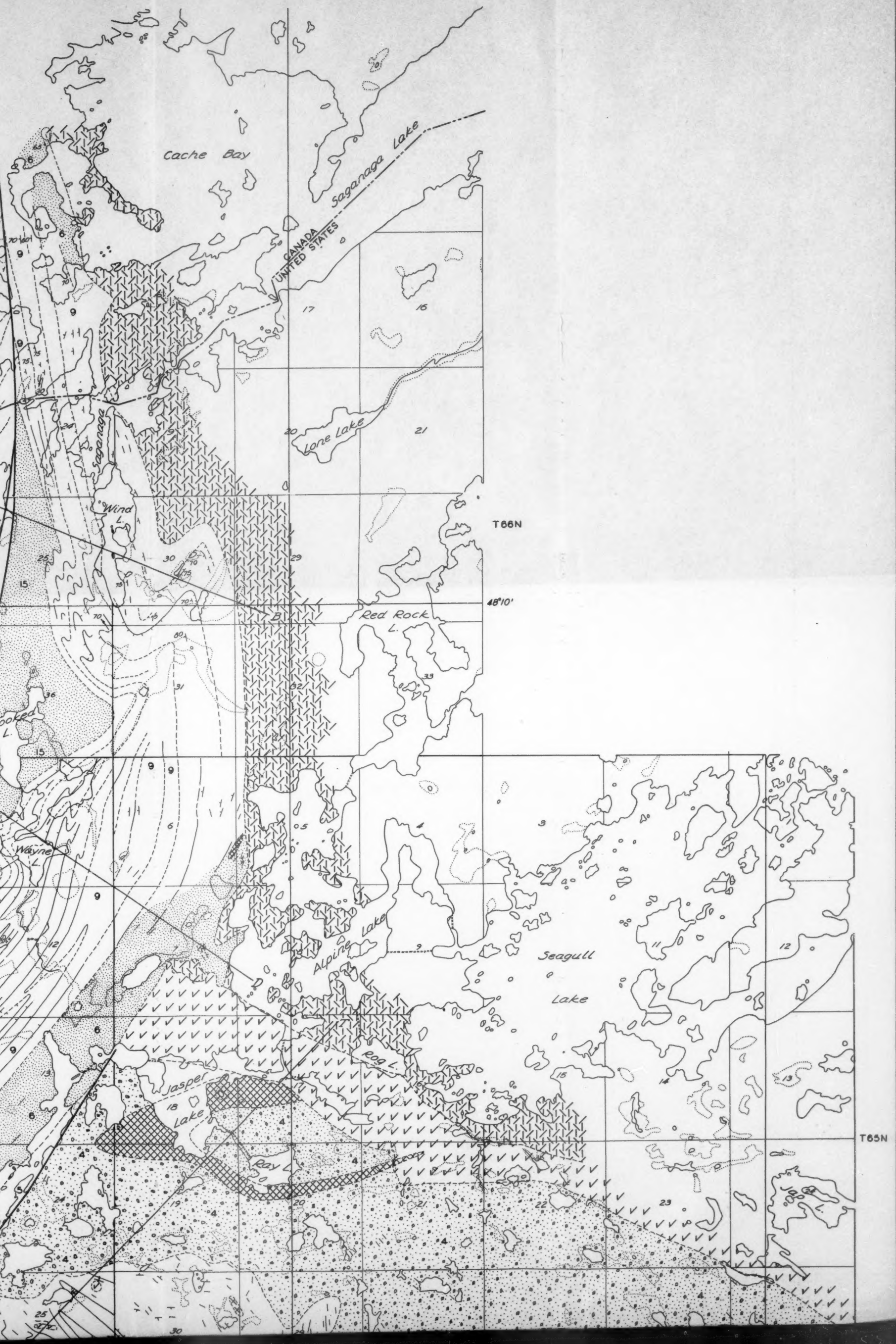
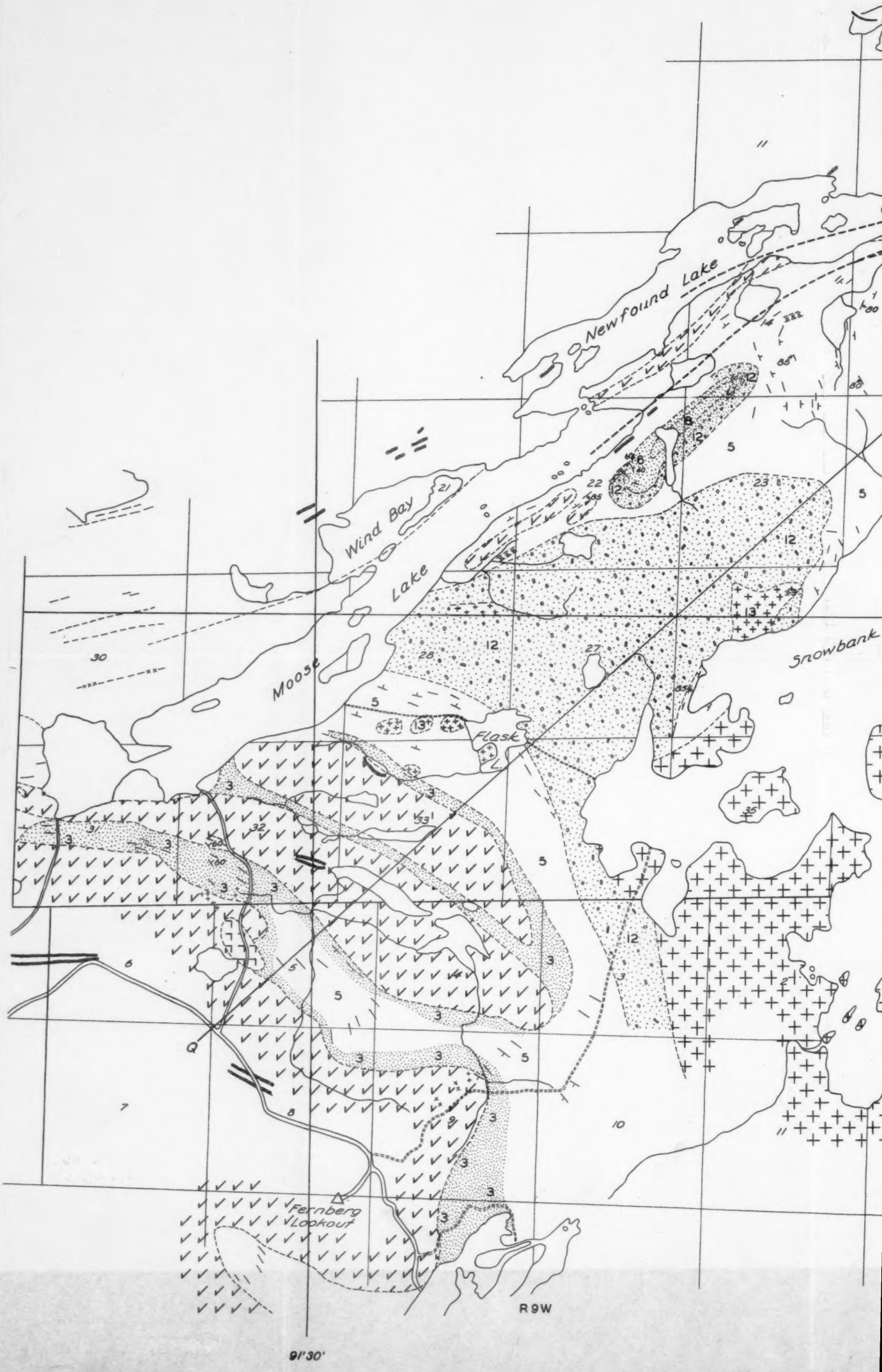

Cache Bay
Saganaga Lake
CANADA
UNITED STATES
Lone Lake
Saganaga
Wind L.
T66N
48°10'
Red Rock L.
Hooked L.
Wayne L.
Alpine Lake
Seagull Lake
Bog L.
Jasper Lake
Ray
T65N


Newfound Lake
Wind Bay
Lake
Moose
Flask
Snowbank
Fernberg
Lookout
R9W
91°30'

CANADA

CANADA
UNITED STATES

Carp Lake

Heron L.

Portage L.

Lake

Birch Lake

Vera Lake

Chute L.

Sucker Lake

Ensign Lake

Bass Lake

Gibson L.

Jordan Lake

Boot L.

Snowbank Lake

Disappointment Lake

Disappointment Mountain

Round Lake

T63N

R8W

91 25'

91 20'

GEOLOGIC

CANADA

CANADA
UNITED STATES

Heron L.

Carp Lake

Portage L.

Lake

Birch Lake

Vera Lake

Chute L.

Arkose L.

Ensign Lake

Bass Lake

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Disappointment Mountain

Disappointment Lake

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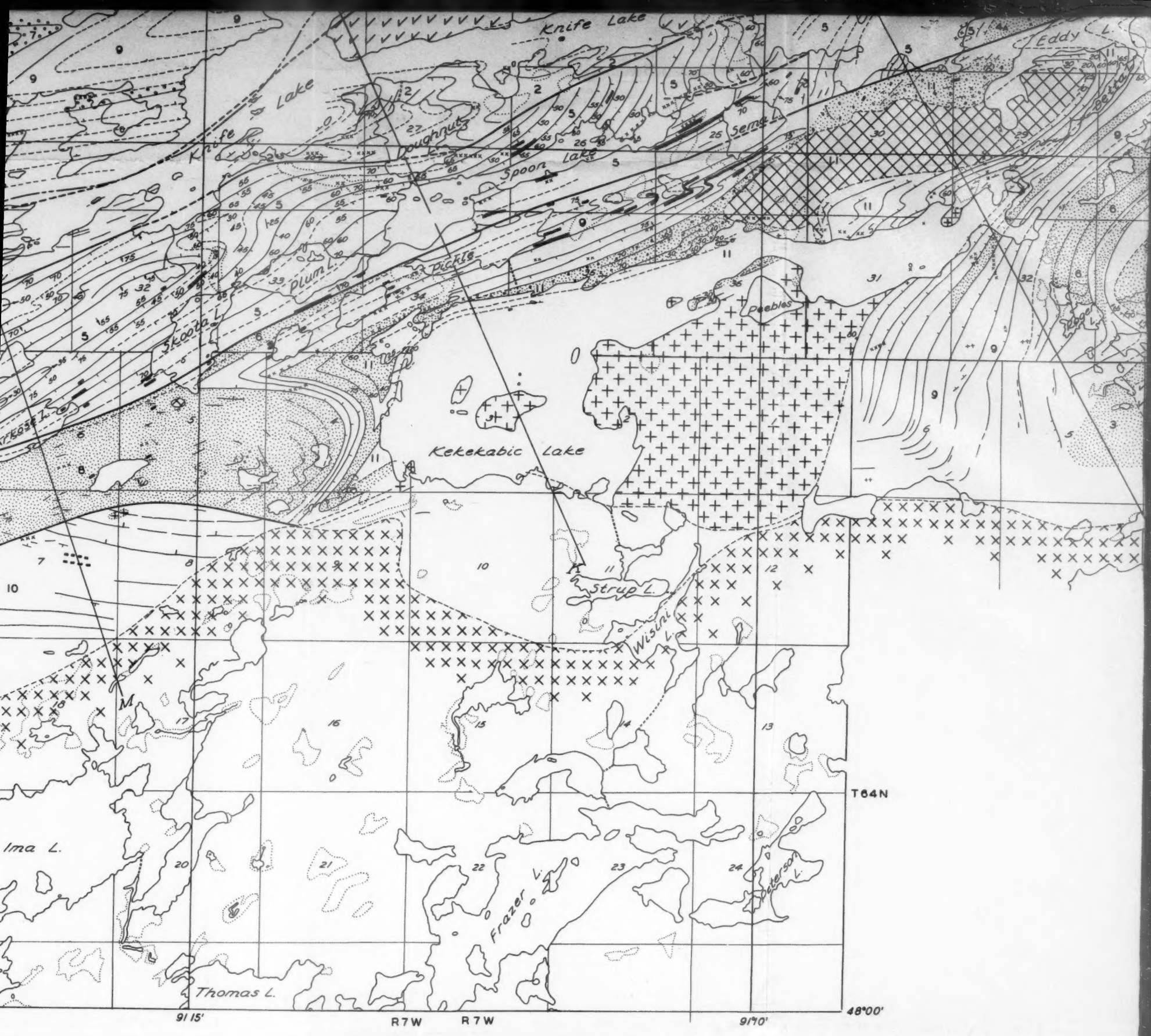
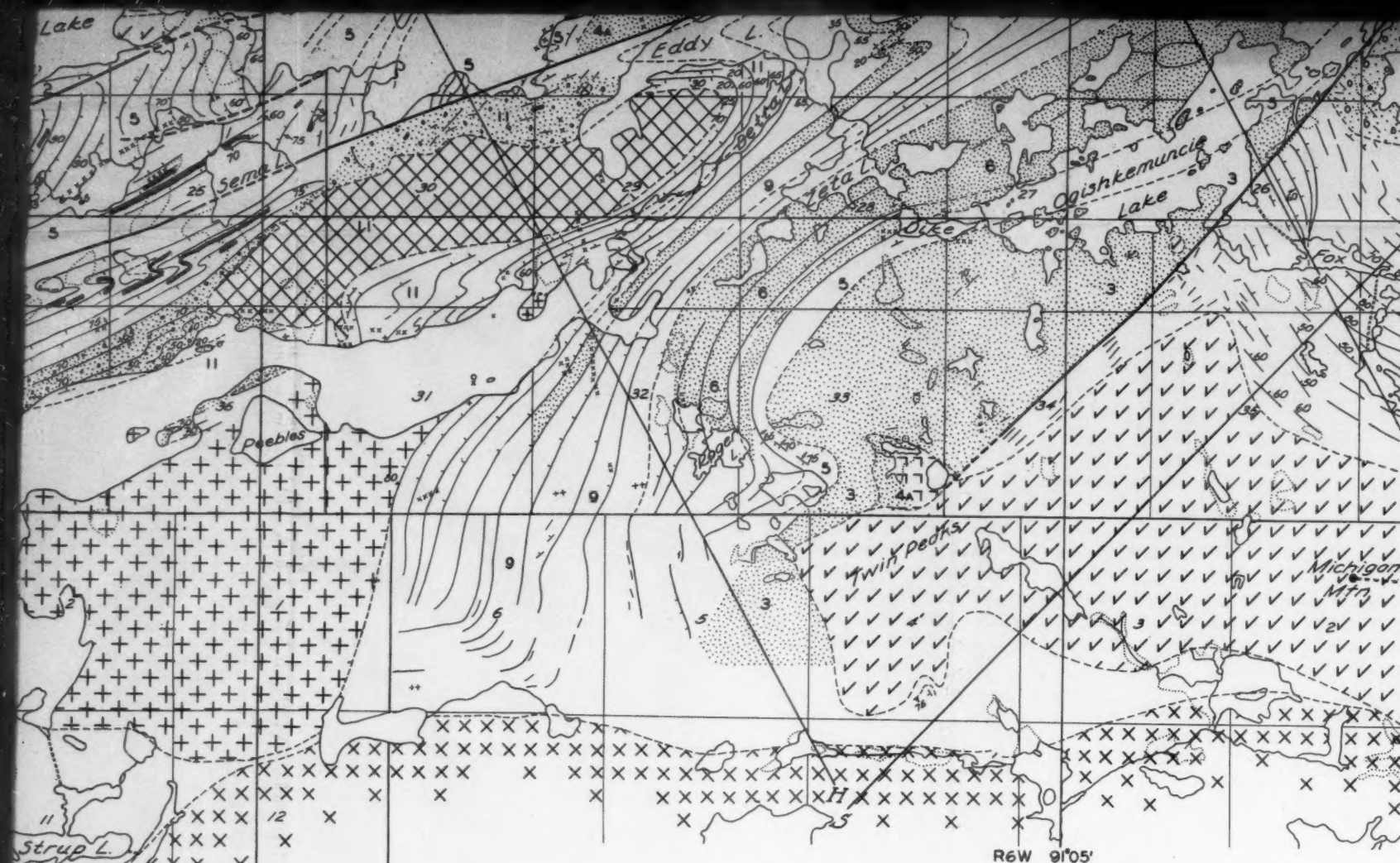


MAP AND SECTIONS OF KNIFE LAKE AREA



ALGONKIAN SYSTEM

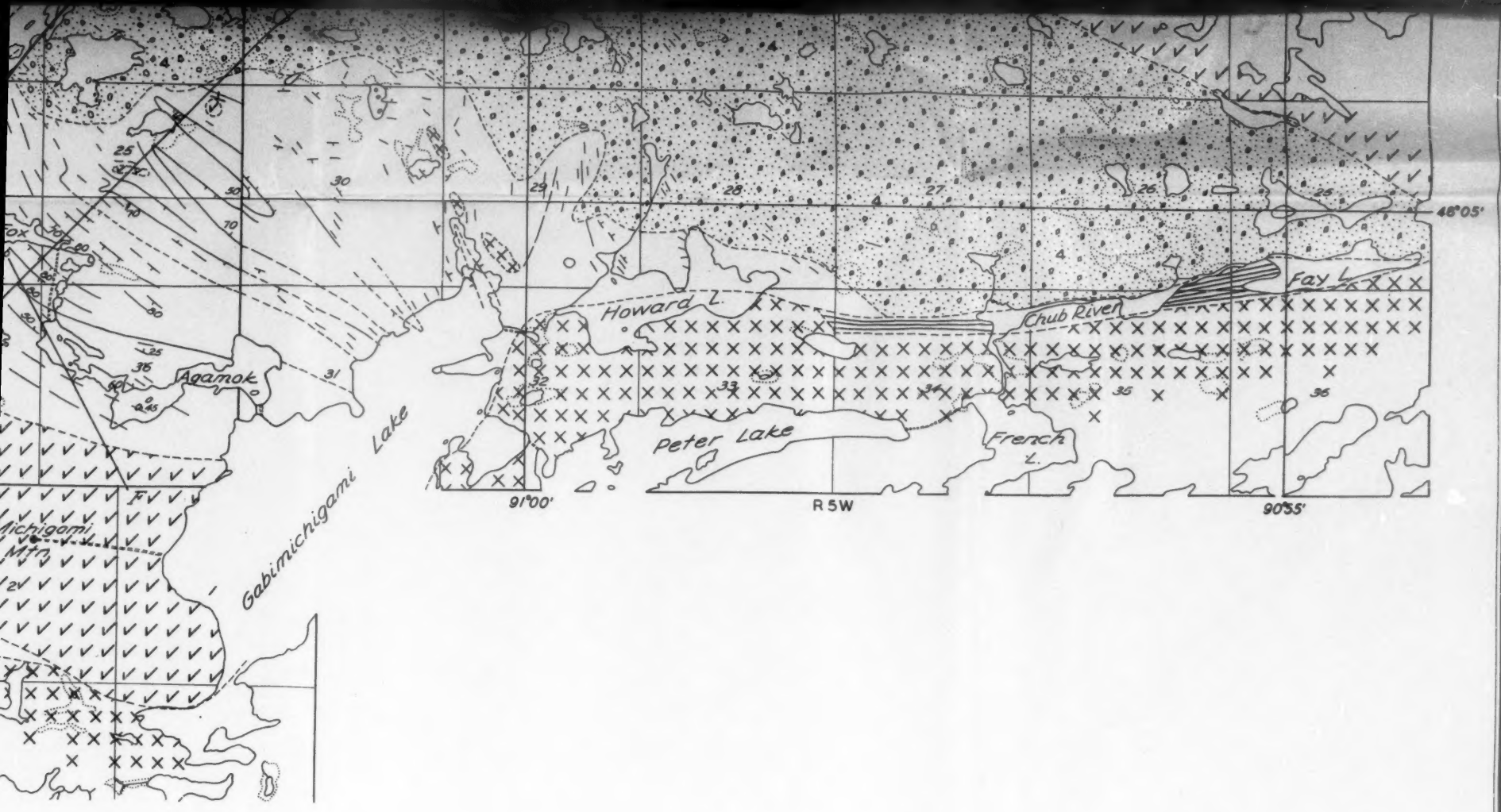
ANIMIKIAN SERIES — KEWEENAWAN SERIES

- Duluth Gabbro
- Diabase Dikes
- Gunflint Formation

ALGOMAN SERIES

- Granites and Syenite
- Hornblendite
- Feldspar Porphyry

NIFE LAKE AREA



LEGEND

ALGONKIAN SYSTEM	KNIFE LAKE SERIES		Lenses of Iron Formation
			Andesite Porphyry 11
			Agglomerates and Conglomerates 4, 12, and parts of 11
			Massive Arkosite and Graywacke 7
			Conglomerates 3, 4a, 6, 8, 15, 16, 18, & 19
			Slates, Graywackes, and Tuffs 1, 2, 5, 9, 10, 14, 17, and parts of 11.
	LAURENTIAN SERIES		Saganaga Granite
			Acid Intrusives and Extrusives
ARCHEAN SYSTEM	KEEWATIN SERIES		Soudan Formation
			Andesitic Intrusives
			Ely Greenstone

- Boundaries of formations and members
- Strike of bedding and probable bedding
- Strike and dip of bedding without indication of the tops of beds
- Strike and dip of bedding with recognizable tops
- Strike and dip of bedding where beds have been overturned
- Strike and pitch of dragfold
- Strike and dip of flow cleavage which probably parallels original bedding
- Fault
- Probable fault
- Swamp with well defined outlines
- Portage

N

GEOLOGIC MAP
OF THE
KNIFE LAKE AREA
OF THE
VERMILION RANGE

PUBLISHED WITH PERMISSION
OF THE
DIRECTOR
OF THE
MINNESOTA GEOLOGICAL SURVEY

BY
JOHN W. GRUNER
IN COLLABORATION WITH C. E. DUTTON
G. R. GIBSON AND F. F. GROUT

1939

SCALE

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BULLETIN OF THE GEOLOGICAL SOCIETY OF AMERICA
VOL. 52, PP. 1577-1642, 5 PLS., 5 FIGS. OCTOBER 1, 1941

STRUCTURAL GEOLOGY OF THE KNIFE LAKE AREA OF NORTHEASTERN MINNESOTA

BY JOHN W. GRUNER

(*With C. E. Dutton, G. R. Gibson and F. F. Grout as contributors*)

CONTENTS

	Page
Abstract	1578
Introduction	1579
Acknowledgments	1580
General description of district	1581
Geography	1581
Topography and drainage	1581
Forests	1582
General geology	1582
Archean system	1584
Keewatin series	1584
Ely greenstone	1584
Soudan iron formation	1588
Laurentian series	1589
Acid intrusives and extrusives	1589
Saganaga granite	1590
Algonkian system	1590
Knife Lake series	1590
General considerations	1590
Basal gray slate and graywacke (1)	1591
Flinty slate (2)	1591
Disappointment Mountain and Moose Lake conglomerate (3)	1592
Jasper Lake greenstone conglomerate or agglomerate (4)	1593
Quartz porphyry conglomerate (4a)	1594
Well-banded slates and graywackes (5)	1595
Ogishke granite pebble conglomerate (6)	1597
Massive arkosites and graywackes (7)	1601
Pink andesite conglomerates and agglomerates (8)	1602
Amoeba Lake graywackes, slates, and tuffs (9)	1603
Ensign Lake green slates, tuffs, and graywackes (10)	1605
Kekekabic tuffs, agglomerates, slates, and andesite porphyry (11)	1606
Ensign-Snowbank Lake agglomerates (12)	1608
Feldspar porphyry intrusions (13)	1610
Ester Lake graywackes, slates, and tuffs (14)	1611
Crooked Lake granite pebble conglomerates (15)	1613
Lower slate pebble conglomerate (16)	1613
Intermediate tuff (17)	1614
Upper slate pebble conglomerate (18)	1614
White pebble conglomerate (19)	1614

Page

Agamok sediments ... 1615
"Agawa iron formation" ... 1616
Replacement zones ... 1618
Algoman series ... 1618
Feldspar porphyry ... 1618
Hornblendite ... 1618
Algoman granites and syenites ... 1619
Animikie series ... 1620
Gunflint formation and Rove slate ... 1620
Keweenawan series ... 1620
Diabase dikes ... 1620
Duluth gabbro ... 1620
Pleistocene series ... 1621
Glacial drift ... 1621
Structure of the Knife Lake district ... 1621
Structure criteria ... 1621
Structural units ... 1622
General statement ... 1622
Segments of the Knife Lake synclinorium ... 1623
Canadian synclinal segment ... 1624
Knife Lake greenstone segment ... 1625
Spoon Lake segment ... 1627
Kekekabic Lake segment ... 1627
Gabimichigami Lake segment ... 1632
Ensign Lake segment ... 1634
Snowbank Lake segment ... 1635
Discussion of structural geology ... 1635
Geologic history ... 1638
Conclusions ... 1640
Works to which reference is made ... 1641

ILLUSTRATIONS

Figure Page

1. Key map showing location of area surveyed ... 1580
2. Page from a field notebook to show complicated folding of "Amoeba Lake graywackes, slates, and tuffs" ... 1604
3. Field notes of excellent drag folds on Ester Lake ... 1612
4. Distribution of structural units or segments in Knife Lake district ... 1623
5. Stages in development of a closely folded synclinorium which is underlain by a competent floor ... 1631

Plate Facing page

1. Geologic map and sections of Knife Lake area ... 1577
2. Slates, tuffs, and graywackes ... 1596
3. Conglomerates ... 1597
4. Conglomerates ... 1600
5. Agglomerate and greenstone segment ... 1601

ABSTRACT

The stratigraphy and structure of the Knife Lake area was investigated in detail. The ellipsoidal greenstone flows are only of Keewatin age. The Knife Lake series

consists of about 10-20 recognizable members. The terms "Ogishke conglomerate" and "Agawa formation," as used formerly, should be discarded.

Conglomerates appear at many horizons in the series. The Knife Lake series consists of continental sediments and contains no major unconformity. There was considerable volcanic activity during the time of sedimentation. Many longitudinal faults divide the area into distinct structural segments. The development of synclinoria resting on the Archean basement complex is discussed, and it is thought that the distance of the folds above this basement can be inferred from the arrangement of the folds.

INTRODUCTION

An enormous amount of geological work has been accomplished in the last half century on the Canadian Shield. The chief stimuli were the desires to find iron and gold ores. The purely scientific objectives of disentangling the complexities of pre-Cambrian rocks was not forgotten, however, as may be judged by the extensive literature. In spite of all this work a greatly detailed structural investigation of a typical area in which the rocks range from Keewatin to Keweenawan in age, is still missing. It was with this objective in view that the present structural study was begun in the summer of 1928. The area chosen was the eastern part of the Vermilion range described by Clements and associates (Clements, 1903). The area is about 30 miles in length from east to west and 10 miles in greatest width (Fig. 1). It is more favorably situated than most other areas because a large portion is almost free from direct intrusive activity of Algoman age. Also, it contains the Saganaga granite mass on its eastern border which is Archean (Laurentian). It includes a sufficient number of greenstone belts and conglomerates to practically prove or disprove the presence of more than one series of greenstone eruptives. The Animikie series is close enough to the southern margin for a study of its unconformable relationship to the Knife Lake series. Also a large amount of previous work by highly competent geologists is available as a basis of a detailed investigation.

The field methods were Brunton compass surveys along closely spaced lines. The scale used in the field notebooks was 222 feet to the inch over a large part of the area. Such a large scale was usually necessary since outcrops in burned-over areas are very numerous. About half the area was burned over 25 to 30 years ago and still offers excellent exposures. The unburned portions contain partly 80-year old second growth and some original forest which make correct geological interpretation difficult. Such areas will be mentioned especially in the report.

The study includes a narrow area north of the International Boundary in Canada, the mapping of which was essential for a correct interpretation of the structures.

ACKNOWLEDGMENTS

During the field seasons of about 7 to 8 weeks each year from 1928 to 1934, the writer had the able assistance of the following men: John Ffolliott, Rudolph Gebhardt, Theodore Bennett, Newton Chute, Gilman

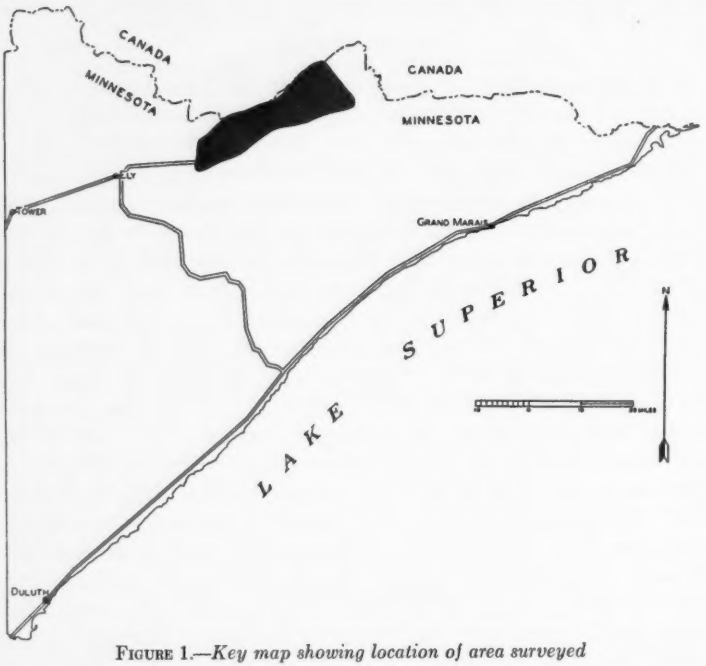

FIGURE 1.—*Key map showing location of area surveyed*

Berg, George Gibson, and William Gardner. In 1935 and 1936 the area was visited for about 3 weeks each year, at which time Messrs. Roger Swanson and Eduard Dobrick ably aided the writer.

Dr. V. G. Sleight was so kind as to let the writer read his thesis, the material for which he had collected in a number of seasons under the direction of Dr. U. S. Grant and Dr. J. T. Stark of Northwestern University. This thesis covers the area surrounding Ogishkemuncie Lake. It had been thought at first possible to incorporate the excellent data in this report as a unit, but it was found on further study that Sleight's data could not be correlated without a complete restudy of the area.

C. E. Dutton and George Gibson studied the area at Ensign and Snowbank lakes for theses and are contributors to this paper, as acknowledged

on the title page. Their work was done in 1929 and 1930, and 1932 and 1933, respectively. Their assistants, Messrs. L. Moon and J. Sturrmans, rendered important service. Dr. F. F. Grout, with the assistance of Dr. Stanley Sundeen, during 1932, became a contributor by his work between Snowbank and Moose lakes and around Disappointment Lake. He also made many helpful suggestions in connection with petrographic studies.

A great deal of detailed petrographic work undertaken in the theses mentioned is omitted from this report in order not to obscure the essentials of the structural part.

GENERAL DESCRIPTION OF DISTRICT

GEOGRAPHY

The eastern half of the Vermilion district described in this paper is a belt (48° N. Lat., 90°50′ – 90°35′ W. Long.) more or less parallel to the boundary between the United States and Canada. The region is accessible from Ely by canoe, and its edges may now be reached by automobile. The geography of the maps was compiled from all former sources, as well as from aerial photographs taken by the United States Forest Service in 1934. These photographs do not include the central region, but the marginal portions only. Inspection of the maps will show at a glance which portions are based on photographs, for in them the outlines of lakes are more detailed. The spelling of the names of the lakes follows that of the U. S. Forest Service which has been approved by the National Geologic Board. Most of the original land section corners and meander corners were destroyed by fire long ago.

TOPOGRAPHY AND DRAINAGE

The district belongs to the vast peneplane of the Canadian Shield. Anyone who views the country from one of the higher points is impressed with its comparative flatness. The enormous number of ridges, cliffs, swamps, and lakes is not visible from such a point. In traversing the district, however, one finds extreme ruggedness the rule. The topography is largely controlled by the structure of the rocks, as is readily discernible on the maps. Whole series of lakes and swamps follow the trends of the folds and faults. The roughest topography is found in the greenstone belts, the smoothest in moderately dipping slates.

The drainage is poor. All the territory drains into either Basswood Lake or Lake Saganaga and from there ultimately into Hudson Bay. Differences in elevation range from 1300 feet at Basswood Lake to about 2000 feet at Twin Peaks and Gabimichigami Mountain.

FORESTS

At one time most of the country was covered by timber, much of which was either logged before 1912 or destroyed by fire. When Monograph 45 was prepared by the United States Geological Survey (Clements, 1903), much of the second growth must have been about 35 to 40 years old for fire had swept the country in about 1860, according to N. H. Winchell. Therefore the old surveys had a better chance to observe the outcrops of certain areas than the present geologists had. On the other hand later fires cleared off sections which had been covered around 1900. There is practically no large commercial timber of any sort in the district now.

GENERAL GEOLOGY

The rocks of the district are of many different kinds. Most types of metamorphic rock are found. Metamorphism ranges from slight to severe. The extreme kind is absent except locally. It was for this reason that this area was selected for study. Most interesting are the metamorphosed conglomerates and agglomerates which had not been mapped closely by the older surveys.

The following igneous, or originally igneous, rocks are represented: Archean greenstone flows and intrusives; andesite porphyry flows and dikes or stocks which are intruded into the Knife Lake series; Laurentian and Algoman granites and syenites; and Keweenawan gabbro and diabase.

The geologic column (Table 1) is intended to show the rocks in their chronological sequence as far as this is possible at present. It will be noticed that in its larger features the column differs only slightly from that published by the United States Geological Survey in 1935 (Leith, Lund, and Leith, 1935). The term Lower Huronian is not applied to the Knife Lake series in this report because if it were the most profound unconformity in the Lake Superior region associated with the Algoman intrusions would divide the Huronian into two parts. Instead of the term "Upper Huronian" for the Gunflint iron formation and Rove slate, "Animikie" is reintroduced. In this way confusion is avoided because Leith, Lund, and Leith (1935) put the Gunflint formation into the Middle and the Rove slate into the Upper Huronian, basing their conclusions on correlations south of Lake Superior. In Minnesota, however, no evidence has been found that the Biwabik and Gunflint formations are separated from the Virginia and Rove slates by any break.

The many different members of the Knife Lake series enumerated in Table 1 are not necessarily all different chronologically as will be shown later. For example, the Ensign-Snowbank Lake agglomerate may be

TABLE 1.—*Geologic column*

	Pleistocene series	Lake beds
		Glacial drift
	Unconformity	
Algonkian System	Keweenawan series	Duluth gabbro
		Diabase intrusions (dikes and sills)
	Animikie series	Rove slate
		Gunflint formation
	Unconformity	
	Algoman series	Algoman granites and syenites
		Hornblendite
		Feldspar porphyry (time?)
	Knife Lake series	Agamok sediments (1)
		White pebble conglomerate (19)
		Upper slate pebble conglomerate (18)
		Coarse intermediate tuff (17)
		Lower slate pebble conglomerate (16)
		Crooked Lake granite pebble conglomerate (15)
		Ester Lake graywackes, slates, and tuffs (14)
		Feldspar porphyry intrusions (time?) (13)
		Ensign-Snowbank Lake agglomerate (time?) (12)
		Kekekabic Lake tuffs, agglomerates, slates, and andesite porphyry (11)
		Ensign Lake green slates, tuffs, and graywackes (10)
		Amoeba Lake graywackes, slates, and tuffs (9)
		Pink andesite conglomerates and agglomerates (8)
		Massive arkosites and graywackes (7)
		Ogishke granite pebble conglomerate (6)
		Well-banded slates and graywackes (5)
		Quartz porphyry conglomerate (4a)
		Jasper Lake greenstone conglomerates and agglomerates (time?) (4)
		Disappointment Mountain and Moose Lake greenstone conglomerates (3)
		Flinty slates (2)
		Basal gray slates and graywackes (1)
	Unconformity	
Archean System	Laurentian series	Saganaga granite
		Acid intrusives and extrusives
	Keewatin series	Soudan formation
		Sediments and pyroclastics
		Andesitic intrusives (time?)
		Ely greenstone

the time equivalent of the Jasper Lake greenstone conglomerates and agglomerates. Since they occur in segments which have not yet been correlated it is impossible to put them under the same heading.

No angular unconformities were discovered in the Knife Lake series notwithstanding the closest search. The writer (Gruner, 1929) thought that he had discovered an additional important unconformity in the district and published a short paper on the subject. After mapping considerably more territory it was found, however, that a number of longitudinal shears or faults had led to a misinterpretation. They had caused the insertion of a narrow belt of greenstone between the sediments in such a manner that the greenstone was mistaken for a later flow. Among other things, the present study shows conclusively that a conglomerate can no longer be used for a dividing plane between series unless it contains rounded fragments which can be positively recognized as having been derived from an older at one time deep-seated rock whose cover could have been removed only by a long erosion interval. Angular unconformities such as that between the Knife Lake series and the Animikie series are of diagnostic value if one of the series is less metamorphosed and truncated beds can be followed long distances. If both are severely affected and both dip at similar high angles it is very doubtful whether any great importance can be attached to this relationship. Faulting can produce a result resembling an unconformity as will be shown later.

ARCHEAN SYSTEM

KEEWATIN SERIES

Ely greenstone.—The Ely greenstone, formed largely by the alteration of basic volcanic rocks, has been described a number of times and probably in greatest detail by Clements (1903, p. 130-172) and by Schwartz (1923, p. 91). Only features necessary for the understanding of its structures are recorded here. Except for exposures in dense forest or in highly sheared areas no difficulty was experienced in differentiating greenstone from greenish rocks of clastic origin. Many greenstones show ellipsoids and spherulites, and these are the chief criteria for identification. Where the massive kinds grade into these types they can be classified with confidence. They are then considered portions of lava flows. Such interpretation is probably correct in most cases, especially where the greenstone occurs in belts as it usually does.

It becomes a matter of more or less speculation in the case of some small masses of originally andesite porphyry which contain neither ellipsoids nor spherulites as to whether they should be classed as Ely greenstone. Some of these bodies are clearly later, as for example the

mass between Kekekabic Lake and Knife Lake which is interstratified with the Knife Lake series. Masses of hornblende andesite porphyry around Jasper Lake in sec. 18, T. 65 N., R. 5 W., are surrounded by agglomerate and conglomerate whose fragments consist chiefly of the same porphyry. These masses were mapped as Ely greenstone by Clements. They are fresher looking than the ellipsoidal greenstones and may be considerably younger; they are the most puzzling rocks of the region.

The six distinct areas of Ely greenstone in the district are

(1) The area immediately to the south and southwest of the Saganaga granite batholith. This greenstone has been metamorphosed to hornblendite and similar rocks by the granite. The metamorphosed phases contribute pebbles to many of the conglomerates of the district. The hornblendite fragments are especially easily recognized. The contact between the greenstone and the conglomerate was studied in great detail south of Sea Gull Lake in the hope of finding evidence as to the two possible relationships of the greenstone to overlying hornblendite conglomerate. If the hornblendite formed from massive greenstone at the time of intrusion at great depth the conglomerate of hornblendite fragments now resting on it was deposited much later. But if the greenstone was eroded at an early age and conglomerate of greenstone pebbles was deposited on it, then the granite might have metamorphosed both to hornblendite. Simple as the problem may appear at first sight, no exposures of the contact between hornblendite and conglomerate could be found because deep ravines occur in critical places. The greenstone becomes highly brecciated in places and is veined by epidote and hornblende, but the same kinds of veins seem to occur in the conglomerate near the contact. Since the area is heavily wooded one cannot be sure that this conglomerate is not a pre-Saganaga fragmental phase of the greenstone. At the outlet of the little lake in the center of sec. 22, T. 65 N., R. 5 W., these veinlets seem to cut quartz porphyry which is so commonly associated with the greenstone. The petrography of the greenstone metamorphosed by the Saganaga granite has been described by Clements (1903, p. 155) and others (Schwartz, 1923, p. 105).

(2) The rock between Gabimichigami Lake and Twin Peaks in secs. 1, 2, 3, 4, and 5, T. 64 N., R. 6 W., is mostly ellipsoidal greenstone. No spherulitic phases were seen. It is slightly greener on weathering than many greenstones, but this may be due to somewhat more green hornblende, probably formed by the metamorphic action of the gabbro to the south. It is evidently more resistant to weathering since it forms the highest ridges. The mass is surrounded by younger slates and

graywackes except on the southwest side where greenstone conglomerate is in contact with it. There are no faults at the immediate contact, though faults are common in the greenstone belts to the north. The contact between slates and greenstone is visible except for a few concealed inches in at least three places on the northwest and northeast sides. The greenstone conglomerates mapped as narrow bands at these places by the United States Geological Survey (Clements, 1903) could not be found.

Between this area and Jasper Lake three small masses of ellipsoidal greenstone outcrop in secs. 24 and 25, T. 65 N., R. 6 W. They appear to be in the middle of anticlines of slate and graywacke. Dense forest growth prevents detailed study, but in the southwestern mass, near the center of sec. 25, the greenstone resembles a dike rather than a flow. It is only about 20 to 50 feet wide. The tops of the slate beds are toward it in places, and there is no shearing at the contacts. The ellipsoids are excellent, and one hesitates to call this mass a dike. On the other hand, the structure suggests an intrusive younger than the sediments. Ellipsoidal structures occur in dikes as has been shown again lately by Stark (1938).

(3) A belt of greenstone 9 miles long lies between the two arms of Knife Lake and extends eastward beyond Hanson Lake. It was mapped essentially correctly by the older surveys except for its eastern extension. The belt is divided in places by infolded outliers of gray slate too small to show on the maps. These may possibly be interstratified with the flows. At the west end on Knife Lake the belt is almost half a mile wide. Here typical ellipsoidal greenstone occurs on the south side but gradually gives way to coarser doleritic rock and at the north it becomes almost like gabbro in texture. A mile to the east the belt loses some of this massiveness and it may be ellipsoidal for its whole width still farther east. There spherulites also become very numerous. The rock weathers to a characteristic dark green which may become a coffee brown along shear zones where much iron carbonate was introduced. Interesting features are brecciated or "exploded" ellipsoids which consist of recemented fragments of greenstone. They resemble pebbles and boulders of conglomerate though on close inspection it is noticed that they could be fitted together to make complete ellipsoids. The cement weathers with a slightly lighter color. The whole resembles a greenstone conglomerate for which it was probably mistaken by Clements (1903, Atlas). He surrounds the whole belt of greenstone with a thin layer of conglomerate which cannot be found by recent detailed study. A very good exposure of this pseudo conglomerate may be seen on the shore in the SE½ of sec. 17, T. 65 N., R. 6 W., where the south arm of

Knife Lake swings toward the north for half a mile. The outcrop is at the very edge of the water. On both sides the greenstone belt is in fault contact with the sediments for much of the way.

In sec. 21, T. 65 N., R. 6 W., a very narrow belt of greenstone outcrops which had been mapped by Clements at only one end and as Keweenawan diabase. It is ellipsoidal and almost entirely surrounded by quartz porphyry or by the conglomerate derived from the latter which in places is indistinguishable from it.

(4) A ridge of greenstone which rises 270 feet above the surrounding country is located in sec. 26, 27, 34, and 35, T. 64 N., R. 8 W. It is usually referred to as Disappointment Mountain. The greenstone mass is flanked by a greenstone conglomerate except on the east side where the Duluth gabbro covers it. North of the central part of the mass there is a massive dark-green medium-grained rock which grades into ellipsoidal rock about 1000 feet south. The ellipsoids average 4 feet in length and 2 feet in width with their long dimensions striking east-west. The ellipsoidal greenstone is about half a mile wide and grades into massive greenstone again on the south side.

Two little knobs of ellipsoidal greenstone were discovered in sec. 17, T. 64 N., R. 8 W. It is very difficult to account for their positions except by faulting on both sides. On the northeastern edge a fault is the only logical explanation because a deep long valley separates the greenstone from other formations. On the southwest the fault shown on the map was traced independently of the greenstone southeastward from Ensign Lake. It does not follow the contact of greenstone and conglomerate but leaves some greenstone conglomerate attached to the greenstone. This gives the impression that this conglomerate is a part of the younger "white pebble" conglomerate outcropping farther to the southwest.

(5) At the northwestern limit of the map area short distances beyond the international boundary ellipsoidal greenstone forms long parallel belts. These belts differ lithologically very little if at all from that between the two arms of Knife Lake except that locally they show the effects of the intrusion of the Basswood granite. For the whole length of Cypress Lake and 3 miles southwest the greenstone is in fault contact with the sediments. Greenstone outcrops south of Big Rock and Emerald Lake and can be followed through Carp, Birch, Newfound, and Wind lakes to the west end of the district. A fault contact probably exists through the last-mentioned three lakes. Near the Basswood granite shearing has been intense, and instead of one continuous fault several parallel faults may exist.

(6) South of Moose Lake a number of ellipsoidal anticlinal greenstone belts strike southeastward. The mapping by Clements (1903) is remarkably accurate for this area, and only slight changes were made in the present investigation. The greenstone belts are separated by conglomerates, graywackes, and slates derived from them. Highly altered andesite porphyries of doubtful age seemingly intrude the greenstone. Considerable effort was made to find out whether they also intrude the sediments, but the exposures were too poor.

The greenstones throughout the district are ellipsoidal. In a number of places in Canada the shapes of these ellipsoids have served the geologists to distinguish the tops from the bottoms of the flows. This criterion unfortunately was not applicable in any part of the present study. The present attitude of the greenstone flows is not known, except by inference from the position of near-by sediments.

Soudan iron formation.—The Soudan iron formation has been described many times because it is one of the most interesting sediments and probably (under different names) of wide distribution throughout the greenstone areas in the Canadian Shield. In the district studied it occurs only at the west end of Moose Lake and along Carp and Cypress lakes. In these localities it is in contact with greenstone at least on one side of its steeply dipping lenses. These are rarely over 50 feet wide and exceedingly intricately folded. As a rule they are much more visibly folded than any other rock. The folding has been described in great detail by Clements (1903 p. 175).

The iron formation now consists chiefly of quartz and iron oxides with minor amounts of amphiboles and occasionally some siderite. It is difficult to understand the intense folding of rocks of this composition. Simple deep burial in the so-called zone of flow should have deformed mineralogically different sediments much more than the brittle iron formation. The real answer to this problem seems to be that deformation occurred when the iron formation consisted of the easily deformed iron carbonate mixed with some chert and probably some tuffaceous material which flowed possibly more readily than ordinary slate, depending upon the ratio of carbonate to chert. Alteration to jaspilite took place after folding or more or less simultaneously. This suggestion is somewhat different from that of Van Hise and Leith (1911, p. 549-555) who thought that the mineralogical change largely preceded the deformation.

As mentioned, some of the lenses of iron formation lie against greenstone only on one side and have sediments on the other. These are not

necessarily of Soudan age as will be pointed out when the so-called Agawa iron formation is discussed.

Keewatin sedimentary rocks may exist in this district. Direct evidence for their presence was not found and probably will not be forthcoming unless one could prove that the Saganaga granite is intrusive into conglomerates, slates, or graywackes.

LAURENTIAN SERIES

Acid intrusives and extrusives.—One finds many whitish-weathering acidic rocks in the greenstone most of which consist of a felsitic groundmass and small quartz or feldspar phenocrysts. The latter may be abundant or almost absent. The porphyries have been described in great detail by Clements (1903, p. 247-252) for the outcrops around Tower and Ely. They are also common at the west end of Moose Lake in the form of long dikes. Farther east on Knife Lake they occur in the greenstones as dikes usually with a strike parallel to the greenstone belts. They are rarely over 100 feet wide, generally much narrower.

In two places stocklike masses occur. The one in sec. 15, 16, and 20, T. 65 N., R. 6 W., is large; its exact dimensions cannot be determined for it is surrounded by conglomerate and arkosite derived from it and resembling it very closely. The same is true of a much smaller mass north of Twin Peaks in sec. 33, T. 65 N., R. 6 W. Clements mentions neither of these but he speaks of the difficulty of distinguishing brecciated and sheared porphyry from true conglomerate, especially on islands in Lake Vermilion (1903, p. 249-251). This difficulty does not exist in the district studied, for shearing is not very common in the porphyry. The porphyry fragments in the conglomerate are well rounded but often exceedingly difficult to observe because the matrix is made up of the same material.

Since these porphyries are never found intrusive in the Knife Lake series they are assigned to the Laurentian. Clements agrees chiefly because fragments of them are found in Knife Lake conglomerates. This is not necessarily a valid reason for lithologically very similar porphyries might be of entirely different ages and could not be distinguished unless they contained some very unusual features which these do not have.

Some of the quartz porphyries must be older than the youngest greenstone for fragments of them—often rounded—have been caught up in the younger greenstone flows. Probably they were not carried very far because they are never seen more than a few feet from where the white porphyry is in place. Fragments of banded gray and black cherty rock are also included in the ellipsoidal greenstone where the porphyry fragments are found. Their relationship was very carefully studied in the SW¼ of sec. 32, T. 64 N., R. 9 W., and in the SE¼ of sec. 17, T. 65 N.,

R. 6 W. In some of these places rounded greenstone and angular chert fragments were found in the porphyries. An indistinct banding in portions of the porphyry gives the impression of water-laid material, and only closest examination will reveal the true relation.

Saganaga granite.—It is possible that the Saganaga granite came from the same magma chamber as the porphyries described as Laurentian. In that case some of the porphyries were probably somewhat earlier than the granite according to the evidence presented above.

The Saganaga granite was intruded undoubtedly at considerable depth and with considerable accompanying orogenic movement (Grout, 1929). Though the exposed portion of the granite is relatively small, it may possibly be of considerable extent under the sediments, though this is not the opinion of Grout (1936, p. 255).

The great importance of the granite in the present study is its contribution to the Knife Lake sediments. These could not have been deposited before a long erosion interval had stripped the cover from the batholith. Fortunately much of the texture of the granite is such that most of its fragments can be recognized with a considerable degree of certainty. Its large quartzes seem to be absent in other granites of the area. Grout (1929) has recently described the Saganaga granite in great detail. He also deals with the mechanics of the intrusion and with the effects of the Algoman revolution on the mass as a whole (1936). The contact of the granite with the overlying Knife Lake sediments dips to the west at angles of 60 to 70 degrees in many places at the western edge of the batholith.

ALGONKIAN SYSTEM

KNIFE LAKE SERIES

General considerations.—This series has been divided into numerous members in this report. One of the most important findings in connection with this investigation is that the Ogishke conglomerate as basal conglomerate has no claim to a separate grouping. The conglomerates which were mapped formerly as Ogishke conglomerate may occur anywhere in the Knife Lake series. Those which are actually resting on pre-Knife Lake rocks are of relatively small lateral extent. It is, of course, impossible even then to tell whether these conglomerates were actually the first Knife Lake sediments chronologically. Slate and graywacke pebbles occur in many of the conglomerates and are an indication that erosion of earlier sediments was going on simultaneously. On the other hand, slate is found widely in direct depositional contact with greenstone but not with granite. The order in which the different members of the Knife Lake series are presented can be only approximately chronologically

correct in view of the numerous large faults which segment the area as shown in the map and cross sections.

Basal gray slate and graywacke (1).—These highly folded and almost featureless rocks are in contact with the greenstones over a large portion of the area. While in many places the contacts may be faults there are numerous exposures where the member lies directly on the ellipsoidal greenstone without evidence of faulting. Under very favorable conditions gradational bedding may be found, indicating that the tops of the beds are away from the greenstone.

The slates are interstratified with and inseparable from the graywacke. The two rocks are dark gray and differ only in grain size. On weathering they become a much lighter brownish gray unless they are rather flinty when they weather to a dirty white. Bedding is rather indistinct or almost absent, unless the slate is flinty. Gradational bedding is rare, and cross bedding was not observed. The rock commonly breaks with conchoidal fracture except where it has become phyllitic, as in the western half of the district. Fracture cleavage is rare.

These rocks are rather soft and often form basins. The best exposures are found along Knife Lake in its largest basin of the north arm north of sec. 14, T. 65 N., R. 6 W., and along the little lakes west of this section in Canada. In sec. 22, T. 65 N., R. 6 W., the gray slates rest against the greenstone which may be in fault contact, though of no great displacement. Beginning at the west line of sec. 28, T. 65 N., R. 6 W., the slates become more cleavable and phyllitic farther west. On Birch Lake and farther southwest chloritic and sericitic phyllites and schists are the rule. The sericitic phase is commonly the alteration product of more flinty varieties of slate. There are no horizon markers in this member, and it would be futile to attempt to map more detail in them even in burned-over areas. Their thickness probably does not exceed 1500 feet.

Flinty slate (2).—The flinty slates are readily distinguished from the dark-gray basal ones. They overlie them in numerous places on Knife Lake and grade into them, sometimes rather abruptly. As they are very dense and hard they form ridges and hills. On fresh surfaces they are medium to dark gray, but they weather to a banded dirty white and bluish gray. The bands are fairly easily visible where folding has not been intense enough to convert the rock to sericitic phyllite. No gradational bedding occurs because the material is almost uniformly fine-grained. Fracture is conchoidal except west of Carp Lake where cleavage may appear. Highly flinty facies of slate may occur as lenses in different horizons in the Knife Lake series, but the member to which the foregoing

description applies begins in sec. 23, T. 65, N., R. 7 W., and follows the south shore of Knife Lake. Farther west it is found between Ensign and Birch lakes. Near the west end of these lakes it is so fissile and sericitic as to be classed as phyllite. Through Newfound and Moose lakes it cannot be traced as a definite unit on account of even more intense metamorphism. The greatest stratigraphic thickness of the flinty slate is considerably in excess of 1000 feet.

In some horizons of the flinty slate thin lenses of an intraformational conglomerate occur which at the most are a few feet wide, in places only inches. The fragments are not over an inch in diameter. All of them seem to be angular elongated slate and graywacke pebbles. A rather local feature is the rather reddish color developed in secs. 5, 6, and 7, T. 64 N., R. 8 W., where a number of granitic and syenitic dikes have intruded the flinty slates. The dikes are offshots of the Algoman granites and evidently had an oxidizing effect.

Disappointment Mountain and Moose Lake conglomerate (3).—While slates and graywackes were being deposited in one part of the district, conglomerate probably formed in others. In the Disappointment Mountain area a conglomerate consisting mostly of fragments of greenstone with a few fragments of jasper overlies the Ely greenstone. The pebbles range from a fraction of an inch to 6 inches in diameter, and vary from angular to well rounded. In some places the rock is almost a breccia. The matrix consists of material similar to the pebbles but finer. Very little stratification is visible. The contact between greenstone and conglomerate is difficult to determine because of the presence of swamps and ravines.

The conglomerate surrounds the greenstone on all sides except on the east where it is covered by the Duluth gabbro. On the north side the conglomerate is separated from an overlying agglomerate by a swamp, and the fragments are quite angular; on the south side of Disappointment Mountain the pebbles are well rounded and some bedding is visible. Metamorphism near the gabbro has obscured the nature of the rock overlying the conglomerate, but it may be a slate. The average thickness of the conglomerate at Disappointment Mountain is about 1200 feet.

South of Moose Lake in secs. 31, 32, 33, T. 64 N., R. 9 W., and secs. 5 and 4, T. 64 N., R. 9 W., a number of almost parallel synclines strike NW-SE. The anticlinal greenstone between the synclines is overlain by conglomerate like that just described. The greenstone conglomerate is only a few to 300 feet thick. It grades into graywacke and slate which contain good gradational bedding. The beds have their tops away from the greenstone.

A very similar conglomerate in the Twin Peaks area lies directly on the greenstone in secs. 4 and 5, T. 64 N., R. 6 W. This is of interest because farther to the northeast gray and flinty slate lies directly on the same greenstone mass, and there is a fault between the slate and the greenstone conglomerate. This conglomerate area reaches to the south shore of Ogishkemuncie Lake and has been called the Moose Lake conglomerate by Stark and Sleight (1939)[1] who thought it basal to the sediments of the Knife Lake series recognizing the fact that the Ogishke conglomerate of the type locality—on the north shore of Ogishkemuncie Lake—is not basal. The name Moose Lake conglomerate was chosen by Stark and Sleight on account of the similarity to that just mentioned as occurring on Moose Lake. There are, however, certain differences.

This conglomerate is uniform over a width of a mile. The pebbles are very largely hornblende andesite porphyry, are usually rounded, though many are quite angular as in the agglomerates to be described. They vary from small sand grains to some 2 feet in diameter. The common ones seem to be about the size of hens' eggs. Visible bedding is exceedingly rare, mostly because the matrix consists of the same rock as the pebbles. It is very easy in some places to confuse this conglomerate and the andesite porphyry. This may have happened in the case of two small areas in sec. 27, T. 65 N., R. 6 W. They are indicated on the map and correspond roughly to two larger ones mentioned and mapped by Clements (1903, p. 304, 321-322) as greenstone. The area under discussion is densely forested, and it is difficult to come to a decision. If they are of Keewatin age they are certainly not typical greenstone but resemble much more the later andesite porphyry found in the Knife Lake series at Kekekabic Lake.

Jasper Lake greenstone conglomerate or agglomerate (4).—This conglomerate though similar to that south of Ogishkemuncie Lake is treated as a separate unit. It extends from Conglomerate Lake in sec. 24, T. 65 N., R. 6 W., to the end of the map area 7 miles to the east. It is most easily studied southeast of Jasper Lake and north of Howard (Paul) Lake. In the latter area a forest fire 25 years ago removed enough of the moss cover to permit the study of the outcrops in more detail than anywhere else. The complexities are great as evidenced by the differences in the map presented by Clements (1903) and the present one. Even on the present map small areas of the conglomerate in greenstone cannot be shown separately on such a small scale. The chief difficulty in the field lies in distinguishing massive hornblende andesite porphyry

[1] Stark and Sleight call this conglomerate "Saddle Bag Lake conglomerate" in the text and "Moose Lake conglomerate" in Table 2.

from the fragmental portions mapped as greenstone conglomerate. The latter may be in large part agglomerate interstratified with andesite porphyry flows. The fragments vary from millimeter size to some 24 inches across. The majority are angular or subangular; in some rocks there is little matrix between them, in others the matrix may be dominant. There is almost no visible bedding or banding. On weathering the material becomes whitish or brownish. The fragments are slightly different in color from the matrix. There are two kinds of fragments: hornblende andesite with phenocrysts (or metacrysts) of hornblende, and dense andesitic ones without any visible crystals. The unweathered rock is always grayish green or bluish green regardless of kinds and sizes of fragments and matrix. In the few places where structure can be observed the strikes are about N. 35° to 60° W., and the dips are steep to the northeast. A very few outcrops show gradational bedding which indicates that the tops are toward the northeast.

Unless one is inclined to accept a thickness of 10,000 to 15,000 feet of conglomerate, he has to assume a repetition of beds due to shallow asymmetric folding as indicated (Pl. 1, cross section S-T). Such folds would consist of alternating gentle and steep dips. All steep dips would be in the same direction and would show the tops in the same direction. Only the steeply dipping beds would be readily seen, as the gentle dips would escape detection in level glaciated outcrops.

This structure would also help to explain the occurrence of andesite porphyry masses in the middle of the conglomerate around Jasper Lake. There the relatively shallow conglomerate was apparently eroded from the flows or volcanic plugs of andesite.

Attention may be called to the observation that no granite pebbles were seen in this area, only some quartz porphyry ones. It may be inferred from this that the Saganaga granite was still unexposed when the conglomerate was laid down. Such an hypothesis makes several other assumptions necessary.

Quartz porphyry conglomerate (4a).—There are two areas where conglomerate consisting almost entirely of quartz porphyry or felsite fragments was deposited probably almost contemporaneously with the greenstone conglomerates. The most extensive of the two lies between the two eastern extensions of the south arm of Knife Lake which has been mentioned already in connection with the white porphyries. It grades from a boulder conglomerate with well-rounded pieces a foot or more in diameter to arkosite. The gradation from coarse to fine in general is from southeast to northwest. Except in good outcrops the porphyry can be differentiated from the conglomerate only with the greatest difficulty.

Both contain considerable pyrite and on weathering become stained with limonite. The exact contact between porphyry and conglomerate is impossible to determine in most places. An interesting occurrence in the conglomerate is a bed of banded green tuff about a foot wide. It is a conspicuous feature on account of the color contrast. It may be easily seen from the canoe along the south shore of the south arm of Knife Lake in the NW¼ sec. 15, T. 65 N., R. 6 W.

As the conglomerate grades into arkosite gradational beds appear with their tops toward the northwest. The arkosite in turn grades into well-bedded graywacke and slate. This succession is exposed well in the SE¼ sec. 17, T. 65 N., R. 6 W.

In sec. 23, T. 65 N., R. 6 W., this conglomerate rests on a mass of quartz or felsite porphyry of indefinite dimensions. The conglomerate and porphyry together are surrounded by greenstone conglomerate except on the southeast side where greenstone outcrops. Whether a fault separates it from the greenstone is impossible to ascertain on account of dense growth and broken topography. In one place the greenstone and quartz porphyry or its conglomerate are separated by a foot of green banded material, probably pyroclastics of the greenstone.

Well-banded slates and graywackes (5).—Under this heading are slates and graywackes which directly overlie one of the members (1) to (4). This member is well bedded and banded (Pl. 2, figs. 1, 2) and shows considerable gradational bedding which enables the deciphering of the folding with a fair degree of certainty. The rocks themselves are difficult to describe. They are gray in the eastern part and more greenish gray toward the west. On fresh fracture there is very little difference between coarser- and finer-grained layers, but on weathering the coarser ones are usually somewhat lighter. The larger the individual grain the lighter it will be, and some are even white. As a whole weathered outcrops look brownish gray. There are occasional grit lenses in the graywackes. The average thickness of layers is probably half an inch. Where there has been considerable shear, as, for example, on the south shore of Spoon and Plum lakes, a phyllitic rock with peculiar bluish green color on weathered surfaces was the result. The distribution of these sediments is as follows:

(1) On the north arm of Knife Lake in secs. 13, 14, 23, and 24, T. 65 N., R. 7 W., the strike of the beds is almost east-west, and the tops are toward the north. The beds are faulted off on the south side, and those remaining are about 2000 feet thick. They grade into arkosic beds toward the north. The beds are a part of the south limb of the great Knife Lake synclinorium, but no corresponding beds have been found

on the northwest limb where faulting has removed them. In Canada, sediments belonging to this member overlie the basal gray slates and graywackes and underlie the arkosic beds. They are somewhat thinner and less easily distinguished from the basal slates.

(2) In the south arm of Knife Lake a very similar unit rests at the east end on quartz porphyry conglomerate and arkosite beds and extends westward as a recognizable unit as far as the west end of Ensign Lake. These beds are highly folded (Pl. 2, fig. 2) and confined by two longitudinal faults on the north and south. The one on the north side was discovered after all the field data had been assembled and it was found that the structures of the flinty slates could not be reconciled with those of the well-banded member. The fault on the north side is really a broad shear zone. West of Spoon Lake there was considerably more metamorphism with much local shearing and production of chloritic phyllites than east of the lake. In this area lenses of conglomerate and grit occur in slates and graywackes. They may be as wide as 15 feet and a few hundred feet long. The predominant pebbles are flinty slate and chert less than an inch across.

(3) The slates and graywackes between Moose Lake and Snowbank Lake, and between Newfound Lake and Snowbank Lake, also seem to belong to this member. They overlie greenstone conglomerate and are overlain by agglomerates. They may be 3000 feet or more thick. The graywackes and slates between Snowbank Lake and Disappointment Lake have a similar stratigraphic position and probably are correlated.

(4) A belt of slate with a maximum thickness of 1000 feet lies on the greenstone conglomerate at Ogishkemuncie Lake. It may be contemporaneous with the well-banded Knife Lake slates and graywackes. It is described by Stark and Sleight (1939, p. 1034) as Dike Lake slate on account of its persistence on the little lake west of Ogishkemuncie Lake. It is conformable with the underlying greenstone conglomerate into which it grades within a few feet. Its upper contact to the north (gradational bedding shows the tops to the north) is thought by Stark and Sleight (1939, p. 1037) to be unconformably overlain by the Ogishke granite pebble conglomerate. They have found a beveling of about 10 degrees on the slate in the NW¼ NW¼ sec. 26, T. 65 N., R. 6 W. The writer was shown these outcrops by Doctor Sleight but he is not inclined to the view that the beveling represents a major erosion interval. Comparison of the map by the writer with that of Stark and Sleight shows some differences west and southwest of Ogishkemuncie Lake. On their map the Dike Lake slate is completely cut out (Stark and Sleight, 1939, p. 103-4). It was followed, however, by the writer toward the southwest and south 1½ miles farther until it finally was lost in the large swamps separating

FIGURE 1. "WELL-BANDED SLATES AND GRAYWACKES" ON DIKE LAKE

FIGURE 2. "WELL-BANDED SLATES AND GRAYWACKES"
With many drag folds in the SE¼ SE¼, sec. 17, T. 65 N., R. 6 W.

FIGURE 3. "ENSIGN LAKE GREEN SLATES, TUFFS, AND GRAYWACKES"
Note pocket knife in center of picture for scale. Many beds show gradation of grains (Gibson, 1934).

SLATES, TUFFS AND GRAYWACKES

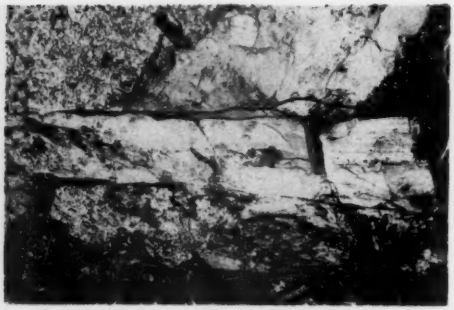

FIGURE 1. CONTACT OF DIKE LAKE SLATE AND OGISHKE GRANITE PEBBLE CONGLOMERATE
On north shore of Ogishkemuncie Lake. Contact retouched in black. Right end of pocket knife in contact with pebble which is partly in slate.

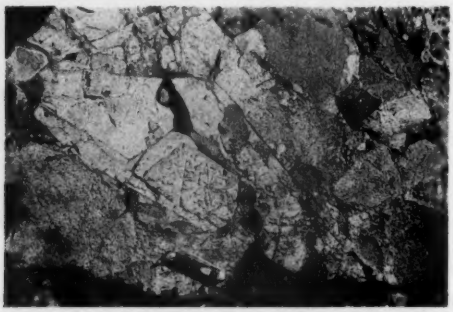

FIGURE 2. "OGISHKE GRANITE PEBBLE CONGLOMERATE" On Ogishkemuncie Lake. Pebbles fairly well rounded, but cobbles and boulders are more angular than usual.

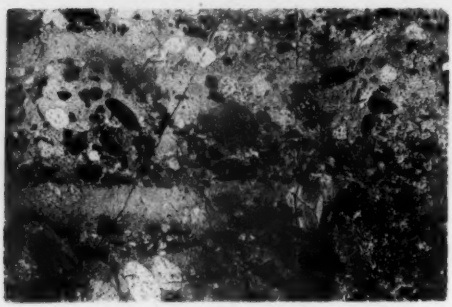

FIGURE 3. "OGISHKE GRANITE PEBBLE CONGLOMERATE" ON DIKE LAKE
Large white pebbles are Saganaga granite. Bedding as shown is common. Imbrication visible in portions of conglomerate.

outcrops of the Knife Lake series from those of the gabbro. Also, the conglomerate which lies on the Dike Lake slate (unconformably according to Stark and Sleight) is separated from the main body of the Ogishke member by another slate lens in no way different from the Dike Lake slate except in size. This lens starts near the northwest end of Dike Lake and can be followed southwestward for about a mile where it gradually fades into graywacke, grit, and conglomerate. Its greatest width is about 150 feet. These beds, like the conglomerate, have their tops toward the northwest. The conglomerate deposited on this slate is just as abrupt and as coarse as that on the Dike Lake slate. As a matter of fact, there are many more instances in the district where a coarse conglomerate is deposited directly on a very fine-grained sediment. In no place, however, was it possible to interpret such a change as an important unconformity. It it true that the angular discordance was observed nowhere except at places pointed out by Stark and Sleight. Even there it seems to the writer to be a local phenomenon, though their paper (1939, p. 1037) gives the impression that the angular discordance can be seen for a fairly long distance in a total extent of 3 miles. The writer "walked the contact" and even removed considerable moss in places. In 1000 feet of total exposure (some poor ones included) there seemed to him little conclusive evidence. In one place on Ogishkemuncie Lake in the NW¼ sec. 27 a pebble was found right on the contact half embedded in the slate. The other half extended into the conglomerate bed (Pl. 3, fig. 1). This seems to indicate that the upper layers were not hardened completely when this pebble was laid down. Induration of a fine-grained layer before the superimposing of another coarse or pebbly one may not indicate the lapse of much time geologically because it is too common an occurrence. Stark and Sleight themselves write that "lenses of graywacke and slate are intercalated with the coarser bands of conglomerate." If the contact represented a major unconformity it would be a very unusual one. It would mean that when conglomerate began to accumulate a nearly horizontal erosion surface of shale (or slate) existed which was parallel to the bedding for miles with the exceptions mentioned by Stark and Sleight. These exceptions are small in area, and the beveling could be explained by local floods during sedimentation, for example.

Ogishke granite pebble conglomerate (6).—The best known beds of this conglomerate are the ones at the type locality at Ogishkemuncie Lake. The Ogishke conglomerate should not be used in the sense of a basal conglomerate as was done in the past (Clements, 1903, p. 297). This rock consists of pebbles and boulders of every kind of rock older than the conglomerate. The Saganaga granite fragments are especially

noteworthy on account of their size and rounding (Pl. 3, figs. 2, 3). Red jasper fragments, green hornblendite, and gray chert or flint pebbles make this rock conspicuous. In the chert pebbles fossil algae were found by the writer in 1922 (Gruner, 1923). The greenstone, slate, and graywacke pebbles are less evident. The matrix is usually grayish green and weathers to a light gray or brown. The bedding becomes visible only where some finer-grained layers are interstratified which is usually the case within a radius of 25 to 30 feet. Stretching of pebbles is not important in this type locality.

The conglomerates usually form abrupt contacts with the formations on which they rest but are transitional upward into finer-grained material. In other words, at the bottom all or almost all beds consist of conglomerate with a few finer-grained beds between; toward the top the finer beds predominate. Also the pebbles may become almost grit size. The conglomerate may grade into finer sediments along the strike. This is not a pinching out but an extension of the same beds as finer-grained layers. Thus it is not surprising that the Ogishke conglomerate member should have all but disappeared along the strike within 3 or 4 miles to the southwest and within 4 or 5 miles to the northeast. This conglomerate is more than 4000 feet thick north of the center of Ogishkemuncie Lake. Gradational bedding shows that all the conglomerate layers have their tops toward the northwest. The petrography of the conglomerates has been discussed in great detail by Clements (1903, p. 3091). He includes in the term Ogishke conglomerate, however, all the conglomerates of the Knife Lake series. Stark and Sleight (1939, p. 1034) on the other hand discuss only the belt at the type locality. They divide it into three submembers on lithological grounds, different kinds of fragments predominating in each member. They write:

> "The Ogishke conglomerate in the area under discussion consists of facies so distinct in varietal character that three separate facies can be readily mapped. Each shows some lateral gradations into the other two, but there is also a rude vertical range with the Peebles or granite facies at the base, overlain by the West Gull or jasper facies and the Zeta Lake or granite porphyry facies at the top."

It appears to the writer that such divisions are local and cannot be differentiated on the map. Stark and Sleight did not attempt it. It is true that on Alpine Lake (formerly called West Gull Lake) in a few outcrops there are more jasper pebbles in proportion than in other easily accessible parts of the conglomerate, as was mentioned by Clements (1903, p. 310). It is an entirely different matter to trace such beds westward. Stark and Sleight think that they are interlayered with their "Zeta Lake facies" near the western half of Ogishkemuncie Lake. The writer followed the conglomerate through secs. 32 and 33, T.65 N., R.6 W., but

could not see any significant differences. The pebbles become smaller southwestward, and ultimately grits take the place of most of the conglomerate. The Ogishke conglomerate was not found to rest directly on the greenstone southeast of Kekekabic Lake, as was stated previously (Stark and Sleight, 1939, p. 1034), but on member (3), the greenstone conglomerate.

The source of the jasper pebbles and smaller grains in the conglomerate and grits has been discussed especially by Clements (1903, p. 310) who thinks that they were derived from the Archean Soudan formation. This is very likely, but it is interesting to note that the proportion of red jasper fragments is much greater than would be expected from studying the remaining exposures of Soudan formation in the Vermilion district, in which white, gray, green, and black bands predominate. Typical banded Soudan formation as pebbles is relatively rare in the conglomerates. No pebble of massive hematite has ever been observed in them.

The question of how much reworked pyroclastic material has been contributed to these conglomerates is difficult to answer. According to Stark and Sleight (1939, p. 1035) the "Zeta Lake facies" of the conglomerate "is a pyroclastic composed of volcanic fragments deposited in water with only slight reworking." There are many conglomerates which have the same pyroclastic appearance not only on Zeta Lake but throughout the district. They are rarely free from layers of conglomerate which had no connection with pyroclastics. Often many well-rounded cobbles and pebbles of granite occur with the otherwise pyroclastic material.

The famous Saganaga granite boulder conglomerate (Winchell, 1899, p. 309) on Cache Bay, Lake Saganaga, may be contemporaneous with the Ogishke conglomerate. It consists almost entirely of pebbles and boulders of granite. It rests directly on the granite and in places it is very difficult to distinguish from granite. It grades into arkosite southward along the strike and westward toward Cypress Lake.

The contact between Saganaga granite and conglomerate or arkosite derived from the granite has been examined by many geologists. Between Cache Bay and sec. 30, T. 66 N., R. 5 W., there are many places near this contact where the only field criterion for distinguishing these rocks is the amount of quartz grains between the granite fragments or the proportion of quartz to feldspar grains. The granite contains a fair amount of large quartz "eyes" fairly uniformly distributed through the mass. The sedimentary material, especially the matrix between boulders or pebbles, contains similar eyes only in larger proportion and concentrated in bunches (Pl. 4, fig. 1). Some pyrite and ferruginous carbonate occur locally in the arkosite, but none was found in the granite. They give

rise to a more brownish yellow color on slightly decomposed surfaces in the sediment. Of course there are places where no difficulties like those in Figure 1 of Plate 4 are experienced. As the fragments become smaller either across or along the strike conglomerate grades into arkosite. Still

TABLE 2.—*Section of arkosite*

About 1000 feet above base of sediments in the SE¼ sec. 24, T. 66 N., R. 6 W.

Top (Inches)		Top (Inches)	
16	arkosite-quartzite	6	slate
5	slate	1	arkosite-quartzite
5	arkosite-quartzite	12	slate
13	slate	10	arkosite-quartzite
18	arkosite-quartzite	4	slate
3	slate	10	arkosite-quartzite
2	arkosite-quartzite	5	slate
½	slate	4	arkosite-quartzite
7	arkosite-quartzite	½	slate
2	slate	15	arkosite-quartzite
4	arkosite-quartzite	5	slate
½	slate	5	arkosite-quartzite
2	arkosite-quartzite	2	slate
1	slate	16	arkosite-quartzite
1	arkosite-quartzite	2	slate
12	slate (banded)	40	arkosite-quartzite
3	arkosite-quartzite	Bottom	

higher the arkosite becomes interstratified with slate and we get a section like Table 2. In the arkosite are many quartz grains, most of them angular; they seem to be identical with those in the Saganaga granite. There is considerable gradational bedding in the arkosite layers, and "scour and fill" in the slaty beds is common.

A granite pebble conglomerate lies on greenstone in secs. 10 and 11, T. 65 N., R. 6 W., east of Hanson Lake. It is the only granite pebble conglomerate where the writer saw the actual contact with ellipsoidal greenstone. It was called Grant conglomerate in 1929 (Gruner, 1929, p. 186). It really does not deserve an individual name for it probably does not represent as long an erosion interval, as was thought at first. Since it lies in a wedge formed by two faults its relationship to other members is obscure. It contains all the kinds of pebbles mentioned for the other belts. Its thickness does not exceed 600 feet, and the transition to graywackes and slates is gradual.

Granite pebbles—not necessarily with large quartz phenocrysts—may be observed in almost any of the conglomerate lenses above the first three or four members of the Knife Lake series. These lenses, often very small, are found throughout the whole district and seem to increase in number toward the top of the series.

FIGURE 1. GRANITE BOULDER CONGLOMERATE
At contact of Saganaga granite in Cache Bay. White spots are quartz eyes about 1/3 inch in diameter. Most outcrops show only faint outlines of pebbles and boulders.

FIGURE 2. SQUEEZED GRANITE PEBBLES AND BOULDERS
Chiefly of Saganaga granite on little island in Ensign Lake (Gibson, 1934).

FIGURE 3. SLATE PEBBLE CONGLOMERATE ON ENSIGN LAKE
Pebbles have been rotated and now are parallel to shear zone of fault. Bedding of sediments runs from right to left (Dutton, 1931).

CONGLOMERATES

FIGURE 1. "ENSIGN-SNOWBANK LAKE AGGLOMERATE"
Showing extremely coarse nature of andesite fragments (Dutton, 1931).

FIGURE 2. "KNIFE LAKE GREENSTONE SEGMENT"
Between two faults (black lines). Looking southwest from the NW¼, sec. 16, T. 65 N., R. 6 W. toward the SE¼, sec. 17. Island in center is greenstone, also hill in background between faults.

AGGLOMERATE AND GREENSTONE SEGMENT

There is, however, a rather persistent horizon of granite pebble conglomerate which may be traced from Plum Lake in sec. 33, T. 65 N., R. 7 E., to Newfound Lake. It is not necessarily continuous, for in some places granite pebbles could not be found. It reaches its best development in Ensign Lake where it is quite similar to the typical Ogishke conglomerate. The chief characteristic is pebbles of coarse-grained granite containing large quartz crystals. On the islands in sec. 8, T. 64 N., R. 8 W., it is composed predominantly of granite and greenstone boulders and pebbles, with some chert and a few slate fragments. The pebbles show squeezing (Pl. 4, fig. 2) and are cut by transverse fractures which are filled with later quartz. Six-inch boulders are very common. The matrix which is largely chloritic is schistose and "flows" around the pebbles. Bedding can be seen only where finer-grained layers are interstratified. The belt on Ensign Lake is about 100 feet wide and is the northern margin of an extremely complicated area of andesite conglomerates described as member (8). It is parallel to a fault zone just to the north.

A rather obscure belt of similar conglomerate is found in secs. 16 and 22, T. 64 N., R. 8. W. It is considerably sheared. The rock appears to be sericite schist in places and can be identified as conglomerate only where the schistosity has not destroyed the outline of the pebbles. Large quartzes apparently derived from Saganaga granite are found in some of the schist in which pebbles can no longer be seen. The pebbles that still remain are greatly distorted. Quartzes are found only within the pebbles and not in the matrix. They seem to be the only primary minerals that are left in the pebbles. The feldspars are completely altered to sericite.

Massive arkosites and graywackes (7).—Throughout much of the region one encounters rocks which might be classed as arkosites by one observer and as graywackes by another for they are intermediate between the two. They are very massive and weather almost white. On fresh fracture they are light to medium greenish gray. Hand specimens look like a somewhat altered fine-grained igneous rock. The feldspars cannot be identified megascopically. Bedding is rare. The rock does not form cliffs, but rounded outcrops as a rule.

One of the best defined belts of this massive rock occurs in secs. 13 and 14, T. 65 N., R. 7 W., and sec. 18, T. 65 N., R. 6 W. It is about 1000 feet thick and grades into banded graywackes and slates below as well as above. It belongs to the south limb of the great Knife Lake synclinorium. On the northwest limb of the synclinorium these beds seem to occupy the bottom of Knife Lake most of the way, but they

crop out on some points and islands. Since they lie along a fault zone they are considerably sheared.

Between Knife Lake and Carp Lake another belt, probably contemporaneous, is thinner but could not be accurately mapped on account of dense forest growth. These sediments are difficult to date but probably correspond to the member of the Ogishke conglomerate. No equivalent beds seem to occur in the Ensign-Snowbank Lake area.

Pink andesite conglomerates and agglomerates (8).—One of the most perplexing problems of this study is the placing in time and equivalency of vast accumulations of andesite porphyry fragmental rocks in the western half of the district. The fragments commonly are pink, and in the field the formation was called "pink pebble conglomerate." The main portion is a conglomerate, but it contains local facies of tuffs and arkosic material. The rock is characterized by pink fragments in a dark-green matrix. The fragments, varying in shape from well-rounded to angular, may be 2 feet in diameter. The average is about 2 to 3 inches. In some places the pebbles are very abundant, whereas in others they are scarce or absent. They are always andesitic.

The largest area of this rock is an east-west belt which begins about a mile west of Kekekabic Lake and ends as a definite unit at the west end of Ensign Lake. It is closely associated on its south or upper side with green andesite agglomerates and tuffs from which it cannot be sharply separated. It is even probable that the two are of the same kind except for the color of the fragments. Clements (1903, p. 319) referred to these conglomerates as greenstone conglomerates and thought the fragments were derived from the Archean basement.

The pink pebble rock lies on the granite pebble conglomerate (6) and at several places contains pebbles of Saganaga granite. It shows no bedding but is much sheared in places. It may be one third of a mile wide on Ensign Lake but narrows farther east.

In sec. 16, T. 64 N., R. 8 W., the pink conglomerate apparently forms a westward-plunging anticline, but the evidence obscured by shearing is so meager that it is not conclusive. The north limb of the structure is underlain by granite pebble conglomerate and overlain by sheared green tuffs and slates. The southwest limb is underlain by volcanic agglomerate, the granite pebble conglomerate being absent. The pink conglomerate has gradational bedding and cross-bedding, both indicating that it is on top of the agglomerate.

The third area of pink conglomerate, in sec. 5, T. 64 N., R. 8 W., forms a lens between gray and flinty slates. Since the contacts are all badly sheared the relationship to these rocks is not clear.

A fourth mass of pink andesite conglomerate occurs in the middle of a small syncline in secs. 14, 22, and 23, T. 64 N., R. 9 W. It is completely surrounded by a band of granite pebble conglomerate. In such an area the numbers attached to the members refer to the character more than to the age. A petrographic description of the pink andesite conglomerate is as follows:

The pebbles are porphyritic with phenocrysts from 1 to 2 mm. in diameter. The primary minerals are andesine, hornblende, sphene, magnetite, and apatite. Secondary minerals are chlorite, sericite, carbonate, and leucoxene. The feldspar forms the most prominent phenocrysts. Zoning is present. Some outer zones are more basic than the adjoining inner ones. The hornblende is green and euhedral. Since some crystals occur within the feldspar the hornblende probably crystallized slightly earlier. The groundmass is a microgranular intergrowth of feldspar and quartz. The pink color seems to be due to disseminated flakes of hematite. The matrix of the pebbles is composed of hornblende crystals and fragments with minor amounts of feldspar, quartz, carbonate, magnetite, and apatite. Most of these crystals are broken and bent. The hornblende crystals are oriented in one preferred direction. The matrix seems to have the characteristics of a tuff.

Amoeba Lake graywackes, slates, and tuffs (9).—These sediments have been named after Amoeba Lake, where they are best exposed. They are only slightly different from the "well-banded Knife Lake" slates and graywackes. They contain more graywacke and considerable tuffaceous material. The latter is not easily recognized in the field unless some angular agglomerates are present too. Lenses of conglomerate consisting of pebbles of all the varieties of previously described rocks are also interstratified. Gradational bedding is common. Conspicuous flow cleavage occurs only in shear zones, and fracture cleavage is relatively rare.

The thickest sediments of this member, about 4000 to 5000 feet, are found in the segment of the Knife Lake synclinorium whose axis passes through Amoeba Lake. Folding is severe. On the maps only the larger folds can be shown, but Figure 2, from a field notebook, illustrates the intricacy of folding. The Amoeba Lake beds overlie the massive arkosites and are overlain by the Kekekabic Lake tuffs, agglomerates, and slates.

On the Canadian side of Knife Lake the same sediments seem to overlie the massive arkosites.

A long and thick belt of similar beds lies conformably on the Ogishke granite pebble conglomerate north of Ogishkemuncie Lake. Its thickness

FIGURE 2.—*Page from a field notebook to show the complicated folding of "Amoeba Lake graywackes, slates, and tuffs."*

is probably close to 2000 feet. These beds grade upward into conglomerates, graywackes, and agglomerates. They contain numerous complicated folds not all of which could be deciphered, especially in sec. 14, T. 65 N., R. 6 W., and northeast of it. Outcrops are scarce in sec. 31, T. 66 N., R. 6 W., and sec. 6, T. 65 N., R. 5 W., and immediately west of these sections. Where dips can be observed they are steep, and the tops of the beds are toward the west. This meager information and the flat topography suggest that the underlying rocks belong to slates and graywackes of the Amoeba member. Some of them may be equivalent to the Ogishke granite pebble conglomerate, which grades into grits and graywackes west and northwest of Alpine Lake. The graywackes and slates west of the arkosites on Swamp Lake on the Canadian boundary may also belong to member 9.

West of Ogishkemuncie Lake the Amoeba Lake member (9) passes through Zeta and Eddy lakes and swings southward to the Duluth gabbro. It is thought that this latter swing was caused by the intrusion of the Kekekabic granite stock. It is likely that the sediments which pass under the gabbro connect with the greenish slates, tuffs, and graywackes at and east of Ensign Lake.

Ensign Lake green slates, tuffs, and graywackes (10).—Green slates and tuffs form a large part of the basin of Ensign Lake and extend eastward to the gabbro. The pink andesite pebble conglomerate is their northern boundary. The southern limit is the gabbro and apparently the same pink conglomerate. Toward the west faulting narrows the belt to an almost insignificant width. It is, therefore, impossible to extend these sediments beyond Ensign Lake to Moose Lake with any confidence. The chloritic phyllites and schists may be at the same stratigraphic horizon.

The usual strike of the green slates and tuffs is close to east-west. The strike of the flow cleavage is approximately parallel to that of the bedding which is well developed on weathered surfaces (Pl. 2, fig. 3). The beds commonly are only a fraction of an inch in width and give the rock a well-banded appearance in the hand specimen. The bands are light and dark green and gray with some pinkish. Where intensity of shearing has been great enough phyllite has been produced. Under these conditions the banding is not conspicuous or is entirely absent.

On the south shore of Gibson Lake in sec. 23, T. 64 N., R. 8 W., a relatively coarse-grained slaty facies shows fracture cleavage superimposed on gradational bedding. The cleavage makes a larger angle with the bedding in the coarser-grained portion than in the finer, which results in a marked curvature of the cleavage. In the fine-grained portion it

is almost parallel to the true bedding. If this phenomenon were mistaken for cross-bedding, as it might be, such beds would be supposed to have their tops in the wrong position (Tanton, 1930).

In sec. 16, T. 64 N., R. 8 W., along the south shore of Ensign Lake, are many outcrops which show banding with green and pink predominating. The bands are usually less than a quarter of an inch wide. In general the rock is very fine-grained but contains some grains of quartz, feldspar, and carbonate up to half a millimeter. The pink color is caused by finely disseminated hematite. The rock as a whole seems to be similar to the Swedish striped "halleflinta" which are now known under the name of leptites (Nystrom, 1922, p. 762-63) and are recognized as water-laid tuffs.

Locally granite and pegmatite dikes have so thoroughly injected the formation as to destroy its characteristic features. Quartz veins from paper thin to 10 feet in width permeate the rock in places. A hornblendite sill intrudes the slates between Ensign and Bass lakes. The effect of the gabbro on the slates and similar rocks has been very considerable and was described by Clements and others (Clements, 1903, p. 342). The proximity of the gabbro is generally shown by the color changes—from light to very dark—of the slates and by the gradual destruction of visible gradational bedding. The thickness of this member cannot be estimated closely on account of isoclinal folding but it may be 4000 feet or more.

The texture of the slates is too fine-grained for mineral identification except under the microscope. Quartz and chlorite are the most abundant minerals. The chlorite shows alignment parallel to the rock cleavage. Considerable amounts of calcite are present as grains scattered through the rock, and in veinlets. The tuffs are interstratified with the slates and graywackes and show little bedding. The principal minerals are hornblende, feldspar, epidote, and magnetite.

Kekekabic tuffs, agglomerates, slates, and andesite porphyry (11).—These sediments lie on the Amoeba Lake member. They are treated separately on account of a mass of andesite porphyry which is apparently interstratified with them on Kekekabic Lake and causes structural complications. The porphyry lies in a syncline because the beds south of the mass have their tops toward it, and the beds north of the porphyry have their tops southward. Grant (1892, p. 55) was the first to describe this andesite porphyry petrographically. This syncline continues westward beyond the limits of the porphyry. The green Kekekabic tuffs and agglomerates surrounding this porphyry are well exposed. One of the best places to study the coarser facies is on the little islands in

sec. 36, T. 65 N., R. 6 W. The rocks are green and disintegrate to a beautiful light-green sandy material consisting chiefly of hornblende. The weathered surfaces are conspicuous on account of peculiar curved erosion surfaces. Furthermore, andesite fragments which are high in carbonates weather more easily leaving hollows and unusual channeled surfaces. Most of the sediments show bedding, and large portions are banded. Others consist of fragments from a fraction of an inch to more than a foot in diameter. The fragments may be well rounded or very angular. They are usually pieces of andesite porphyry or tuff with conspicuous hornblende phenocrysts. Dense and flinty-looking green fragments and pieces of red jasper also occur. The green fragments weather lighter than the matrix which consists of finely triturated material of the same rock. Occasionally a pebble or boulder of granite is found. The angular material is unquestionably an agglomerate whose fragments may change along the strike into rounded water-worn material, producing a conglomerate. Across the strike such changes occur abruptly. Thick masses may thin out in a very short distance, and tuffs and slates may take their places. Shearing may obliterate all signs of former bedding.

Grant (1892, p. 23) was probably the first to recognize their character. Clements, on the basis of observation that they were close to greenstone and therefore represented anticlinal areas, called them greenstone conglomerates. In this area Clements (1903, p. 136, 319), however, incorrectly mapped the andesite porphyry flow or sill as Archean when as a matter of fact it is much younger. It clearly lies on top of the sediments on the shores of Eddy Lake. Examination shows that the shape of Eddy Lake is caused by the synclinal structure. The sediments dip under the porphyry at the south and west shores of Eddy Lake at angles as low as 15°. Where the dips are steeper along the southern margin actual contacts and a local metamorphism to black dense hornfels can be seen. This baking does not exceed a few inches in the tuffs in sec. 30, T. 65 N., R. 6 W. In places it is difficult to distinguish the massive porphyry from the fragmental facies even in burned-over country.

West of the porphyry on the north shore of Kekekabic Lake Grant and Stark (personal communication), as well as the author, have mapped the continuation of the beds which here form the slightly overturned north limb of the Kekekabic synclinorium. The strike of the beds is nearly parallel to the lake shore. Dips are mostly steeply north. Gradational bedding and excellent cross-bedding are common and make interpretation of the structure certain. The writer has followed these sediments farther west and finds that they swing southward completing a structural depression which was intruded by the Kekekabic granite.

Stark (personal communication) has mapped a similar structure on the west side of Kekekabic Lake.

In the great Knife Lake synclinorium this member is represented by thick tuffs and agglomerate-conglomerate beds. These as close folds

TABLE 3.—*Section of tuff, agglomerate and slate*

Near the northwest corner of sec. 9, T. 65 N., R. 6 W.

Inches	
24	tuff, medium grain (top of section)
2	slate *
24	tuff, coarse to fine
15	tuff, medium to fine
18	slate and fine grained tuff, contorted layers
8	tuff, medium to fine
28	slate
18	tuff, medium
7	slate
30	tuff, coarse in middle of layer
15	slate
14	tuff, medium
1	slate
36	tuff with large agglomerate (2 inches max.) fragments
15	tuff, fine to medium, well banded
40	tuff, coarse with fragments (2 inches max.)
15	tuff, fine with slaty bands
6	tuff, medium
10	tuff, fine with slaty bands
20	tuff, medium
4	slate
12	tuff, medium to coarse
4	slate
13	tuff, coarse
8	tuff and slate, very irregular banding
48	tuff, coarse with fragments (2 inches max.)
	Bottom of section.

* Most of the fine-grained tuff and slate layers show some folding or wavy lines.

extend from Cyprus Lake to the south arm of Knife Lake. The layers consist largely of fragments of andesite porphyry which frequently weathers with hollows. This weathering becomes conspicuous just at the water line of lakes. It is difficult to delimit this member of the series upward since transition is gradual. A section typical of such gradation is given in Table 3.

Ensign-Snowbank Lake agglomerates (12).—In the Ensign-Snowbank Lake area the same kinds of agglomerates are very extensive, but it is difficult to correlate them with those just described. They are later than the slates around Snowbank Lake. The stretch between Boot Lake and Disappointment Mountain is the most difficult to correlate with regard to age. It is highly probable that it belongs between (5) and (6).

The agglomerate has the same general appearance throughout the Snowbank area. It is dark greenish gray on a fresh surface and a light gray on the weathered one. A characteristic feature is its lack of uniform texture and structure. Though it appears homogeneous on a fresh surface, when weathered it may appear massive, fragmental, or banded. The agglomerate also contains a number of "blow-outs" and dikes of feldspar porphyry.

Bedding is indistinct, and gradational bedding is very rare. In practically all occurrences the agglomerate overlies slates and graywackes. This slate is probably missing north of Disappointment Mountain on account of faulting. Granite pebble and pink andesite conglomerate seems to overlie the agglomerates in several areas. Whether these conglomerates are contemporaneous with the Ogishke granite pebble conglomerate is doubtful.

The thickness of the agglomerate is extremely variable; 4000 feet is probably a maximum. In sec. 13, T. 64 N., R. 9 W., on a high hill which used to support a triangulation tower, the rock contains large (12-inch) and small angular fragments in a coarse-grained matrix. The fragments are pieces of andesite, diorite, and massive tuff (Pl. 5, fig. 1).

Good exposures are also found on the east arm of Boot Lake. The agglomerate here forms high cliffs on the faces of which are large light-colored fragments in a somewhat darker matrix. The angular fragments attain a diameter of 18 inches. Small white feldspar crystals 1 millimeter in diameter are scattered through the fragments but are considerably more abundant in some than in others. Under the microscope phenocrysts of oligoclase and orthoclase were seen. Only a few corroded quartz crystals with strain colors were noticed. Considerable calcite is present in veinlets. Pyrite as metacrysts is also found.

At the southeastern end of Little Disappointment Lake the formation grades to a conglomerate. Outlines of pebbles 1 to 2 inches in diameter are common. Rounded grains of quartz 3 mm. in diameter weather out in relief in the pebbles. A thin section of one of the pebbles shows as principal minerals quartz, orthoclase, oligoclase, apatite, and magnetite in graphic groundmass. The matrix of the pebbles contains, besides feldspar and quartz, chlorite. Calcite is abundant as veinlets.

In the eastern part of sec. 22, and the western part of sec. 23, T. 64 N., R. 8 W., the agglomerate is banded. A weathered surface shows a froth-like appearnce in the matrix, but where the rock has spalled off, due to forest fires, a peculiar banding can be seen. These bands are not continuous but are composed of fragments aligned in one direction. The thickness of a band is about an inch, and the fragments may be 2 to 6 inches long. Some fragments have the appearance of having been

squeezed since they thicken and thin and conform somewhat to the shape of those above and below them. Schistosity in the matrix bends around the fragments. The fragments are of lighter color and appear to be siliceous. One, studied under the microscope, contains andesine, orthoclase, quartz, and hornblende. Secondary minerals are chlorite, quartz, and biotite. The feldspar crystals are ¾ mm. in size, and the quartz grains are slightly larger. The groundmass is too fine to be determined. The origin of the structure is problematic, but the fragments possibly suggest the breaking of crusts of lava and engulfing of the fragments in the still molten portion.

The agglomerate in sec. 30, T. 64 N., R. 8 W., and around the west end of Disappointment Lake is faintly pink on weathered surfaces which may be attributed to the oxidizing action of the Snowbank granite. The fragmental character of the rock is conspicuous. Hornblende crystals can be seen in the hand specimen and are probably secondary since they occur in both matrix and fragments. Near the Duluth gabbro the fragments take on very irregular shapes with veinlike extensions reaching into the matrix and also matrixlike material veining the fragments. The large mass of agglomerate between Moose and Snowbank lakes is very similar in appearance to that of Boot Lake.

Feldspar porphyry intrusions (13).—A feldspar porphyry occurs as small masses of "blow-outs" and dikes within the agglomerate. The "blow-outs" are roughly circular and approximately 150 feet in diameter. The rock weathers white with visible white and pinkish feldspars 3 mm. in diameter in a gray matrix. Clements mapped the porphyries in the vicinity north of Disappointment Mountain as offshoots of the Snowbank granite, but they are probably earlier, as shown by the following evidence. In sec. 22, T. 64 N., R. 8 W., the agglomerate and porphyry are sheared and somewhat schistose. Since the shearing took place some time before or at the time of the intrusion of the Snowbank granite, which is not sheared, the porphyry must be the older. In the central part of sec. 21, T. 64 N., R. 8 W., there is an offshoot of the Snowbank granite, while 300 single paces north a small mass of porphyry outcrops. The appearance of the granite is very fresh and decidedly different from that of the porphyry.

Pebbles of these porphyries seem to occur in the white pebble conglomerate (19) which is intruded by the granite. Further evidence of their age is found on the northwest side of Snowbank Lake where aplite dikes of the Snowbank stock cut the porphyry. Since the porphyry cuts no member of the Knife Lake series younger than the agglomerate it probably is not much younger than the latter.

A thin section of the porphyry shows good porphyritic texture with phenocrysts 3 to 4 mm. in diameter. These are predominantly feldspar, probably orthoclase and albite. Other minerals are quartz, a ferromagnesian mineral, sphene, and apatite. The groundmass consists of quartz and feldspar. Calcite is abundant as veinlets. The feldspars are much altered to sericite and kaolinite, but they will have an index lower than balsam and some show albite twinning. The ferromagnesian mineral is completely altered to chlorite and epidote but its elongated outline suggests that it was either hornblende or biotite before alteration.

Ester Lake graywackes, slates, and tuffs (14).—In the Knife Lake synclinorium we find a great thickness of graywackes, slates, and tuffs above the Kekekabic tuffs and agglomerates (11). Conglomerate lenses and some agglomerates are also present. These beds have been studied in great detail on Ester Lake where they show exceptionally clear drag folds on a large scale. They could be mapped most accurately on the burned stretch between Ester Lake and Amoeba Lake. It was also here that the key structure of the whole synclinorium was discovered.

The typical slates of these sediments do not cleave readily but break with conchoidal fracture. They are dark gray on fresh fracture but weather lighter. The beds are usually less than an inch in width. On fresh fracture bedding is very inconspicuous if not invisible. The coarser-grained beds are somewhat wider and lighter in color. Any of the beds may thin out and really are lenses a few feet long.

Lenses of conglomerate are apparently numerous though it is difficult to form an estimate of the ratio to other sediments. They may be as wide as 20 feet but usually are much thinner. The average size of pebble is less than 1 inch with occasional ones 3 inches in diameter. Most pebbles seem to be graywacke and greenstone, some are slate and granite, but not necessarily with large quartzes. Chert and white porphyry are also common. Small pebbles of red jasper occur in some beds. None of the fragments show effects of squeezing. The larger the pebbles the better rounded they are as a rule.

The graywacke beds are not easily described. They may approach and grade into grit on one side and slate on the other. The graywacke usually weathers whitish to dirty brown.

Between the tuffs and graywacke layers thin bands of red jasper may be found. Some of these could be traced for half a mile though usually they are much shorter. They are the only *red* jasper beds that were observed in the Knife Lake series.

This member (14) must be at least several thousand feet thick. A closer estimate is not possible because somewhere near Ester and Cypress lakes the folds of the synclinorium, which west of this place pitch

northeast, pitch southwest. In other words, the bottom of the synclinorium is in this neighborhood and complicates the interpretation of the structure.

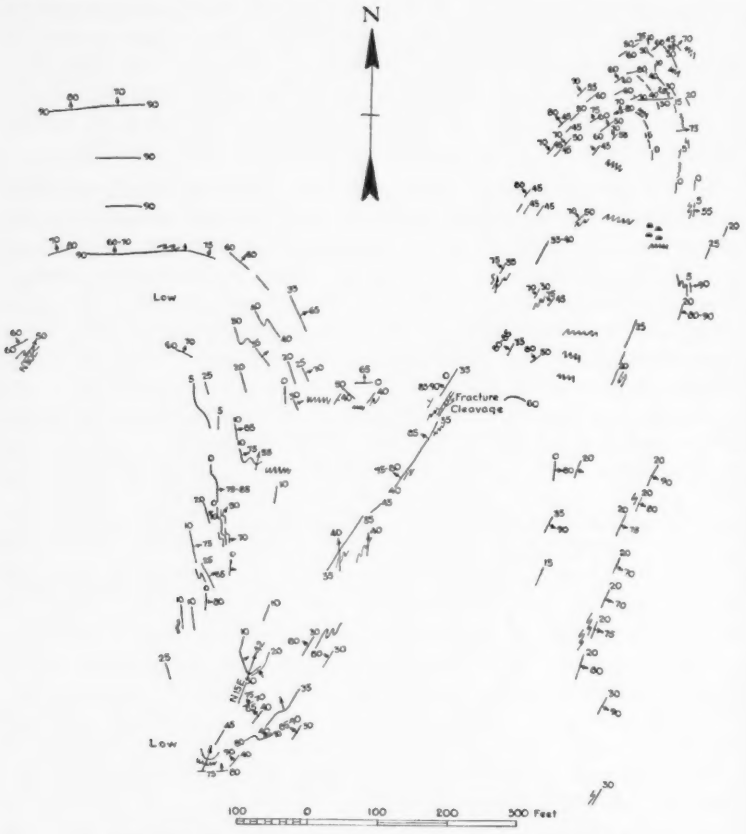

FIGURE 3.—*Field notes of excellent drag folds on Ester Lake*
The writer knows no better example in which all structure criteria except cross-bedding can be observed.

In order that the student may appreciate the complexity of the drag folds a few pages of the field notes are reproduced in Figure 3.

Directly overlying these strata and inseparable from them are apparently massive featureless graywackes that skirt the main arm of Cypress Lake and are faulted against the greenstone. Since they show no gradational bedding and very few dips, their folding is rather obscure.

Some thick conglomerate lenses occur in them. It is possible that low dips could explain the apparent lack of structure, but dense forest covers much of the area.

Crooked Lake granite pebble conglomerates (15).—On the arkosites and graywacke which rest directly on the Saganaga granite there were deposited, abruptly, huge conglomerates which reach a thickness of nearly three-fourths of a mile, or half that much if the conglomerates are folded isoclinally over their width in sec. 36, T. 66 N., R. 6 W. The abruptness of change from graywacke to conglomerate is so conspicuous that it was at first suspected to be due to an unconformity. Much time was therefore spent to find out the true relationship with the conclusion that deposition though abnormal shows no measurable break. The formation lithologically is much like the Ogishke granite pebble conglomerate but shows an important textural difference. It seems to retain its coarseness throughout its whole width. Some 12-inch Saganaga granite boulders are about as common in the middle or the top of the conglomerate as at the bottom. Such boulders are of exceptional size, and the average diameter is closer to 2 to 3 inches on all the numerous outcrops seen. The topography of this belt is peculiar. It consists of closely spaced rounded knolls and short ridges 15 to 20 feet high. On the western margin the conglomerate is limited by a fault. Hardly any strikes and still fewer dips could be discovered. No appreciable shearing and no elongation of pebbles by pressure are noticeable. The area is thickly wooded, but even where outcrops are continuous as on Crooked Lake little structural detail is available.

Among the latest sediments were those in a syncline between Ensign and Snowbank lakes in secs. 17, 18, 20, 21, and 28, T. 65 N., R. 5 W. The syncline is well defined, with a southeast strike and a pitch in the same direction. In this respect it is almost parallel to the Agamok syncline. The sediments of this syncline have been studied by Dutton (1931) in greatest detail; he divides them into the following members:

Lower slate pebble conglomerate (16), coarse intermediate tuff (17), upper slate pebble conglomerate (18), and white pebble conglomerate (19).

Lower slate pebble conglomerate (16).—The slate pebble conglomerate overlies considerable thicknesses of agglomerate described as member (12). The formation occurs as a synclinal belt of conglomerate in which primary sedimentary structures are sparse except for well-rounded pebbles. The pebbles are commonly less than 2 inches in diameter and include black and gray slate, gray chert, diorite, red jasper, massive tuff, and white granitic ones. The granite pebbles are the largest. The slate,

tuff, and chert fragments are the most abundant and give the rock a mottled greenish-gray color on a fresh exposure and a brown color on weathered surfaces from which the pebbles usually protrude due to greater resistance to weathering. The tuff pebbles are flattened ellipsoids, the granite and slate pebbles are subrounded, but the diorite pebbles are angular. The cement of the conglomerate is as variable as the larger constituents and is mostly the same kind of material in smaller sizes. In the vicinity of the fault near Ensign Lake the cement approaches a sericite schist in appearance, and the pebbles are decidedly lenticular. They may also be oriented almost at right angles to their former bedding planes as shown in Figure 3 of Plate 4. At different places along the belt the proportions of the several kinds of pebbles vary. The thickness of this belt reaches 350 feet.

Intermediate tuff (17).—This rock, which overlies the lower slate pebble conglomerate, has few distinguishing characteristics. The constituents may be angular or subangular and are commonly smaller than ⅛ inch, though they may reach a diameter of 1 inch. They are white, gray, or brown, and the rock as a whole shows a granitoidlike texture. In some exposures where matrix and fragments are very similar, the latter show very indistinct boundaries. Feldspar and hornblende crystals can be recognized in matrix as well as in some fragments. Practically no bedding is visible. The tuff may reach a thickness of 1000 feet.

Under the microscope it is composed predominantly of andesine (?) laths about 0.15 mm. long, some hornblende, chlorite, quartz, and epidote. The feldspars are dusty and show little twinning. The matrix is so fine-grained that it appears almost totally isotropic between crossed nicols.

Upper slate pebble conglomerate (18).—These sediments overlie the Intermediate tuff conformably in the same syncline. They are so similar to the Lower slate pebble conglomerate that they might be mistaken for it. They do contain more banded jasper fragments, however. These beds are gradationally bedded and since they can be traced along the strike completely around the syncline they supply the information necessary for structural interpretation. The greatest measured thickness of this member is 350 feet.

White pebble conglomerate (19).—This conglomerate contains mostly pebbles which weather white. It is the youngest formation in this part and perhaps in the whole of the district. It is everywhere underlain by the Upper slate pebble conglomerate. It weathers with a light color and is massive in appearance. Outlines of pebbles can be seen in many

outcrops where vegetation has been removed. The best exposures are those which have been washed by waves such as on the shores of Boot and Disappointment lakes and Snowbank River.

Prominent pebble bands about 2 feet wide alternate with bands of grit and graywacke. Gradational bedding is well developed in the finer beds. The pebbles range from less than an inch to rarely 6 inches in diameter with well-rounded forms, especially in those above 2 inches. The smaller ones tend to be lenticular parallel to the strike of the beds. They have the appearance of elongation due to pressure, but the larger pebbles do not confirm such an explanation. Some imbrication (Pettijohn, 1930) of the pebbles was noted though not on an extensive scale. The pebbles are granite, tuff, graywacke, feldspar, porphyry, and slate. The matrix is composed of the same material in smaller grains. Well-formed hornblende crystals several millimeters long are numerous both in matrix and in the granitoid pebbles. In some places the hornblende is so abundant as to give the rock a dark appearance. It is probable that contact effects of the Snowbank granite were responsible for the crystallization of the hornblende. In the immediate vicinity of granite and pegmatite dikes the conglomerate is pink, giving outcrops a granite-like appearance at a distance. Veinlets have turned the rock pink for several inches on each side. Where these are numerous the whole rock assumes a pink color. Though the conglomerate as a whole is the least metamorphosed of any members of the series in the western half of the district, it is isoclinally folded. The stratigraphic thickness is close to 1500 feet.

Examination of thin sections shows that the matrix is composed of crystals and fragments of feldspar, hornblende, and very fine-grained quartz in an intergrowth with feldspar.

Agamok sediments.—These beds have not been successfully correlated with any of the sediments described, though it seems that the sediments were among the earlier ones to form. They are, therefore, treated separately in this report.

They do not make up a lithological but structural unit as they form a synclinorium which strikes about S. 60° E. between Ogishkemuncie and Gabimichigami lakes. Almost any of the members of the Knife Lake series described above might be represented by lithologically equivalent beds in this synclinorium, but there is no means of correlation because of the dense forest cover. They could antedate the Knife Lake series if it were not for the fact that some pebbles of Saganaga granite are found in the conglomerate layers which are interstratified with the slates and graywackes in the NE. ¼ sec. 30, T. 65 N., R. 5 W.

"Agawa iron formation."—The "Agawa iron formation" which has been described especially by Clements (1903, p. 324) has really no claim to a special name and may not exist as a formation at all. It does not occur at a definite horizon in the Knife Lake series and except on Lake Agawa it is never more than a very few feet thick. It is very lean as far as iron content is concerned. Much of it is jasper or chert with hardly more than traces of iron oxides and siderite.

In the district under consideration and probably in the Canadian Shield in general, there existed a tendency for deposition of ferruginous chert on a small scale through most of Knife Lake time. Almost anywhere in the series there may be small bands or lenses of chert, some containing iron oxide layers. Siderite or ankerite was also precipitated, but usually in other sediments and not as pure beds. Iron carbonate and chert may have been the original precipitate from which the banded jasper and chert developed, but the tendency to deposit ferruginous material persisted throughout all of Knife Lake time.

Some of the "Agawa formation" of the older surveys (Clements, 1903, p. 329) is really a replacement. A striking example discovered in 1925 on the east shore of Ogishkemuncie Lake in secs. 23 and 24, T. 65 N., R. 6 W., is a lens of supposed Agawa formation more than 1500 feet long and several hundred feet wide in a shear zone of a big fault. The rock is made up of iron carbonate, chlorite, sericite, and quartz and is weathered conspicuously to a chocolate brown along the lake shore and on several small islands. This zone actually cuts across the beds of the Agamok syncline in many places and replaces them by iron carbonate. It also replaces portions of the Dike Lake slates adjoining the fault zone.

Similar cases of probable replacement occur along the fault which separates the Knife Lake series from greenstone along a line extending from the west end of Cypress Lake to and through the Canadian portion of the north arm of Knife Lake. Three small lakes occur along this fault zone between the two large lakes. At the narrows in the middle of the northeasternmost lake and also at the fault three fourths of a mile north of the narrows which connect the main Knife Lake with Little Knife Lake are two highly instructive series of outcrops.

Across the strike gray slates and graywackes grade into bands which show more and more replacement by iron carbonates and chert. These in turn become replaced by iron oxide and jasper bands as the greenstone contact is approached. In their final stages they resemble Soudan formation very closely. White quartz veinlets penetrate and cut the replaced portion of the slates and are probably related to the replacement. Pyrite is present as cubes. The width of the replacement zone

may be a few feet or reach as much as 150 feet or more. Shearing is pronounced in places. Another instructive case which was mapped by Clements as Soudan formation occurs at the east end of Carp Lake, where an old Canadian Ranger cabin stands on iron formation. Here the jaspilite is quite thick and intricately folded. It also seems to grade into slate southward.

The true relationship of replacement is difficult to observe because: (1) Due to shearing, low places are filled with water along critical zones, as between the slates and the iron formation; (2) development in the replacement zone may not have gone so far as to produce conspicuous jaspilite bands; and (3) development is only local along contacts.

Replacement by carbonate is not confined to the sediments. In places somewhat shattered greenstone which still shows good ellipsoids is replaced by iron carbonate along definite zones. One of the best exposures of this kind is found in the E½ sec. 23, T. 65 N., R. 7 W., on a little island in the south arm of Knife Lake, where banded formation was not formed, because the replaced greenstone was devoid of original bedding. The genesis otherwise is not very different, however. In a good many respects these ideas on the origin of the banded iron-bearing rocks coincide with those of Collins, Quirke, and Thompson (1926, p. 73) for the Michipicoten iron ranges. The time of replacement in some of these cases may have been soon after deposition of the original rocks or it may have been much later, even Algoman.

In three places along the north shore of Cypress Lake and along the three little lakes between Cypress and Knife lakes, already mentioned, a peculiar porphyritic rock seems adjacent to and parallel to the iron formation. It lies between it and the greenstone proper, where all three rocks could be observed. It is a very coarse-grained feldspar porphyry in the form of dikelike masses possibly as much as 100 feet wide. The andesine phenocrysts are almost white and often 2 inches in diameter. Unfortunately this rock always occurs at the water's edge and against cliffs so that its possible genetic relationship to the iron formation could not be studied. The porphyry can be studied on the Canadian shore of Cypress Lake and on one of the little islands north of sec. 30, T. 66 N., R. 6 W.

That some of the "iron formation" beds are not replacements is shown by Stark (1929, p. 536). He describes in detail the fine-grained tuffs between Spoon and Kekekabic lakes. Their hematite and magnetite layers are interstratified with the tuffs. Since there has been recrystallization it is difficult to find out how much of the material has been of a clastic origin and how much, if any, was a chemical precipitate.

Replacement zones.—Shear zones in the Knife Lake series and the greenstone are very common. However, some show considerable replacement by ferruginous carbonate and quartz. They are not confined to any particular formation or member but may cut through conglomerates, tuffs, or slates with equal effect. In graywacke or tuff they produce an alteration which in the field could be mistaken for an altered porphyry or felsitic rock if it were not that sharp contacts cannot be found. On a slightly weathered outcrop the zones are stained somewhat by hematite and limonite, and vugs are seen which originally were filled with carbonates and pyrite. The unweathered rock shows much silicification, secondary ferruginous carbonate, and some pyrite. Whether chlorite and sericite are among the alteration products depends on the original rock. Carbonate is a common constituent far beyond megascopically visible alteration in the field and has been described many times, especially by the Canadian geologists. By some it is thought an early product of alteration connected with the volcanic activity to which the tuffs owe their origin; by others it is ascribed to the effect of Algoman intrusions.

The writer believes the altered zones result from Algoman activity for it is evident that they could not have originated before the folding was practically completed. They are so common and yet indefinite in outline that they could not be shown on the maps. Some are between 1000 and 2000 feet in length. Their widths are rarely over 200 feet. Their strikes follow the strike of schistosity or rock cleavage. Mineralization in the form of minute veinlets of quartz, carbonate, and pyrite is common. Occasionally short milky quartz veins a foot wide are found. Assays of gold were made in sheared zones. One channel sample has 0.10 oz. of gold per ton, but most of them were much lower. In the Canadian bay of Carp Lake mineralization is pronounced in these zones and carries much purple fluorite and small amounts of sphalerite. The gold content is negligible.

ALGOMAN SERIES

Feldspar porphyry.—The feldspar porphyry which occurs as small masses or "blowouts" in the Knife Lake series has already been described. It is found only in the western half of the district. While most of this porphyry is probably earlier than the end of Knife Lake deposition it is realized that some of it may be of Algoman age and related to the Snowbank granite. It is, therefore, mentioned at this place.

Hornblendite.—A ridge of dark-green dense rock of hornblendic composition occurs in sec. 14 and 15, T. 64 N., R. 8 W., between Ensign and Bass lakes. It contains numerous small dikes of aplite. The mass is 1½

miles long and has a maximum width of about 500 feet. Its north and south boundaries are parallel to the strike of the slates which is approximately east-west. The dip of the sediments appears to be vertical. Gradational bedding indicates that the tops of the beds are northward south of the hornblendite. On the north side the relationship is not clear. It is probable that the mass was intruded as a sill.

The hornblendite has a granitoid texture. The essential minerals are hornblende (70 to 90 per cent), microcline, orthoclase, quartz, magnetite, and apatite. This mineral list is essentially that of the granitic dikes cutting the basic mass, but the proportions of the minerals are very different. The hornblendite is sheared in places especially at the west end and, therefore, probably was intruded before the main granite masses which caused regional metamorphism.

Algoman granites and syenites.—There are two stocks of Algoman acidic rock in the district. The Snowbank stock, described in detail by Sanders (1932) and others (Balk and Grout, 1934), intrudes all the rocks of the Knife Lake series. In composition it is a hornblende granite to syenite. Its effect upon the invaded rocks in places is very severe. Many dikes genetically related to the stock are found in the Knife Lake series. A conspicuous feature in the neighborhood of such intrusions is a reddening of the intruded sediments. This may be observed well in sec. 8, T. 64 N., R. 8 W., where a number of narrow dikes of pink biotite granite have intruded the slates. The red color is not just a surface feature but penetrates the rock. The minute hematite flakes which cause the color may be due to hydrothermally oxidized iron carbonate. Much carbonate is present in both the dikes and slates.

Another smaller granite stock is found 6 miles east, cropping out along the shores of Kekekabic Lake. It was studied in detail by Grant and by Stark (1927). A number of syenitic dikes and pipes are found some distance from the main mass.

The Basswood granite mass, which is a part of the Vermilion batholith, comes closest to the district under consideration on the north shore of Sucker and Newfoundland lakes. Here it has so affected the sediments that it was considered hopeless to attempt structural mapping of them.

In sec. 8, T. 65, N., R. 6 W., near its northeast corner, on the highest hill in this vicinity, a narrow pegmatite vein only 4 inches wide was found. It consists of pinkish microline and quartz. This vein is mentioned particularly because the slates and tuffs at this point of the Knife Lake synclinorium theoretically should have a thickness in excess of 7000 feet, unless the magma from which the pegmatite originated has invaded the syncline as a stock or pipe at this locality.

ANIMIKIE SERIES

Gunflint formation and Rove slate.—Only a very narrow belt of Gunflint iron formation is found in the district. It may be traced from sec. 34, T. 65 N., R. 5 W., eastward to the end of the map area. The Rove slate occurs in patches between the Gunflint formation to the north and the gabbro to the south. The Animikie here dips about 20° to 30° S.

KEWEENAWAN SERIES

Diabase dikes.—Many diabase dikes of Keweenawan age occur in practically all the older rocks. They have been petrographically described by Clements (1903, p. 423). They are always brown on weathered surfaces and almost black when fresh. The grain is medium to fine as observed in the field. At the contact for a width of an inch or two the rock may be very fine-grained. In places the dikes are so prominent that they attract attention from a distance. In other places, apparently in no way different as far as the country rock is concerned, they may easily be overlooked. They are rarely over 50 feet wide and usually only 5 to 30 feet. They are commonly nearly vertical. Some of them are almost straight and can be followed for miles, but most of them are covered for considerable distances, and the outcrops though apparently in line may not belong to the same dike. In one place on a little reef in Knife Lake, in the SW¼ sec. 18, T. 65 N., R. 6 W., a small dike can be seen in vertical cross section. It shows various offsets and does not break through the overlying rock in this place. Since the magma followed the path of least resistance it is evident that such offsets must be common in dikes where some joint crack or fissure became too tight, and another offered easier access. An offset, therefore, does not necessarily mean that a dike was later faulted. Stark (1927, p. 732), however, has found a number of faults across such dikes. About as many dikes follow the bedding (and rock cleavage which is usually almost parallel to the bedding) as cut across the beds. The north-south dikes seem to be the longest.

Duluth gabbro.—The gabbro lopolith is the south boundary of the area. It lies on the truncated edges of the Knife Lake series and has metamorphosed these rocks. In some places the dip of the contact, usually not over 5° to 10°, is exposed. In places on Gabimichigami Lake in sec. 29, T. 65 N., R. 5 W., it must have been almost horizontal, for an erosion remnant of gabbro extends for almost a mile northward away from the main mass. No evidence was found that the gabbro was in any way responsible for any of the structural features of the Knife Lake series.

PLEISTOCENE SERIES

Glacial drift.—Glacial drift covers some parts of the area but at few places reaches a thickness of more than a few feet. Many outcrops, especially slates, were almost polished by the glaciers and show striations which run from northeast to southwest.

STRUCTURE OF THE KNIFE LAKE DISTRICT

STRUCTURE CRITERIA

The criteria employed in unraveling the structure of the region, in the order of usefulness, were:

(1) Horizon markers, (2) gradational bedding, (3) cross-bedding, (4) drag folds, (5) scour and fill, (6) "scalloping", and (7) fracture cleavage.

Horizon markers of great length are absent, but agglomerate layers weathering with peculiar hollows were used for this purpose over distances of several miles. Lenses of conglomerate, arkosite beds, and bands of red jasper proved useful over distances of a mile or two.

Gradational bedding has been of great help. It is well developed in a number of members of the Knife Lake series and practically absent in others. Where it occurs with cross-bedding the two criteria always confirm one another. Cross-bedding, where developed, was greatly relied upon. The only place where it occurs to any great extent is north of Kekekabic Lake. Drag folds are usually very helpful, not only by showing the positions of the anticlines and synclines, but also by indicating in some measure the distance the observer is away from the main crests and troughs. Experience has taught the writer that the closer a given outcrop is to the crest or trough of a major fold the more numerous are the drag folds, other conditions being equal. On long limbs, however, they may be almost absent, or, what is worse, contradictory.

"Cut and fill" proved expedient, but it is uncommon notwithstanding indications of rapid changes in deposition of totally different beds each from one to several inches thick. It would be thought that with so many grits and conglomerates between slaty layers the latter would have been sharply cut and eroded in many places producing "scour and fill," but few have been observed.

A new, but uncommon, kind of criterion was discovered by Dutton. It looks like ripple marks at first glance. Close inspection shows that it occurs only in slates and is connected with neither ripple marks nor mud cracks. As in ripple marks it has a concave side which is always toward the top of the beds. The writer believes that it has some connection with differential expansion or shrinkage of adjoining layers before

complete consolidation. For want of a better name it was called "scalloping."

Fracture cleavage is poorly developed and rarely of any important help. Often days of traversing would not produce one example that could be used for the interpretation of structure. A rare case of fracture cleavage in which the cleavage can be confused with cross-bedding has been mentioned under Ensign Lake member (10). True flow cleavage was more of a hindrance than a help. Wherever it is found it strikes about N. 60° to 90° E. and dips steeply, more often to the south than to the north.

Strike and dip observations on bedding may be exceedingly numerous in places and almost absent in others. They are indicated on the maps where plentiful.

Where outcrops are sufficiently numerous to trace the beds the latter are shown as full lines on the map. Under water and in other places where direct observation was impossible, broken lines have been used. The dips are almost vertical in most places. If they are steeper than 80° the degrees are not especially indicated on the maps for a change of a few degrees either way from vertical has rarely any significance in a very highly folded region unless it is consistent over a larger area. They were, of course, recorded in the field notes. If the average dip is toward the same side as the tops of the beds and less than 80°, dip readings are indicated.

STRUCTURAL UNITS

General statement.—The structure of a district involving rocks of the Archean and Algonkian systems is always expected to be extremely complex. It is often assumed that complications are so great that they cannot be solved. The writer believes, however, that much depends on the amount of time that can be spent in an area. In the district here mapped, if only half as much time had been given to the area it is very doubtful whether more than one or two faults could have been discovered. Without the others, however, the interpretation of the geology would have been either wrong or impossible. No faults at all had been found previous to 1925. An inspection of the present maps reveals a number of long major faults which can be traced throughout the district and some shorter ones which are essential for the interpretation of the geology. There are undoubtedly many others. For example, Grant and Stark (Stark, 1927) have mapped small faults in the Keweenawan dikes on Kekekabic Lake. These have not been included in this report because they have a horizontal displacement of only a few feet and have apparently no important influence on the structure of the highly folded sediments.

The major longitudinal faults divide the district as a whole into long segments or belts, each one distinct in itself, but very difficult, if not

impossible, to connect stratigraphically with any of the others. (*See* Figure 4.) When a unit of structure is completely delimited by faults it is left to one's imagination how it ever reached its present position, possibly by great displacements measurable in miles horizontally and thousands of feet vertically. In some of the segments the displacements

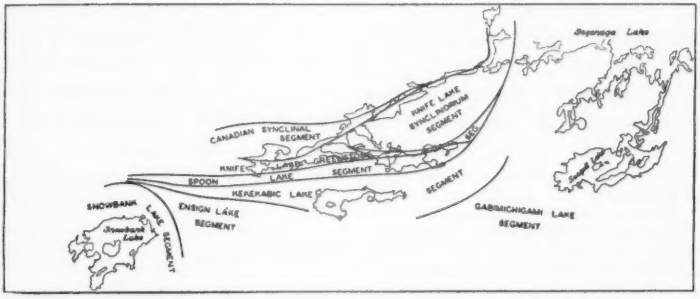

FIGURE 4.—*Distribution of structural units or segments in Knife Lake district*

can be estimated; in others, however, they would become mere speculation. The best way of describing the structure seems to be the treatment by segments. This plan will be followed as far as possible. Those segments whose structure is best known will be discussed first (Fig. 4).

Segments of the Knife Lake synclinorium.—This segment is situated largely between the two arms of Knife Lake, Cypress, Hanson, and Ester lakes. It was possible to study half the area in great detail because second growth forest was not too dense. Outcrops are large and numerous in this portion. Folding is very close, and the best typical drag folding is exemplified by the folds on Ester Lake. A small part of them is shown in detail in Figure 3. This area is well suited for instruction of advanced students in geology.

The segment as a whole is a synclinorium pitching toward the northeast for three-fourths or more of its length (not counting any portion west of Knife Lake). Its axis curves from a strike of N. 80° E. at the west to N. 20° E. at the east. The northern part shows a reversal of pitch.

The pitch of the axes of individual drag folds, where exposed, seems rather steep, commonly about 50°. As pointed out in an earlier paper (Gruner, 1929), this observation gives rise to the tendency to plot greater average pitches than are justified. It is believed that the average pitch of the axis of the synclinorium does not exceed 25°. The axis is not

a straight line but because of cross folding is a composite made up of low and high pitches arranged in steps. In flat country the low pitches are inconspicuous because the limbs of isoclinal folds are nearly parallel. High-pitch angles cause the folds to be visible in cross section. Conspicuous breaks also occur at the noses of steep folds and overemphasize the importance of this steep component. The beds of the limbs of the folds are occasionally overturned 10° and locally as much as 40°.

The stratigraphic thickness of the sediments of this segment is probably close to 15,000 feet. If this thickness is correct, then the bottom of the folds could be from 3 to 4 miles deep in the vicinity of Ester Lake. The sequence and thicknesses of the beds would be somewhat as follows:

	Feet
Ester Lake graywackes, slates, and tuffs	2000-4000
Kekekabic tuffs, agglomerates, and slates	2000-4000
Amoeba Lake graywackes, slates, and tuffs	4000-6000
Massive arkosites and graywackes	1000-2000
Well banded Knife Lake slates and graywackes	2000-4000
Basal gray slates and graywackes	500-1000
Greenstone (?)	

The basal gray slates and graywackes, member (1), seem to lie directly on the west end of the greenstone mass in sec. 22, T. 65 N., R. 7 W. In other words, the long fault which delimits the Knife Lake synclinorium on the south probably dies out at this end, or the throw of it is very small where basal slates are in contact with greenstone. Toward the east the displacement increases and becomes of first magnitude on Hanson Lake. A downthrow of the sediments of 10,000 feet is possible here. Though the eastern part of the segment was enormously depressed, the horizontal component of movement is probably small. The fault to the north produced a very similar effect at the northeastern end of Knife Lake and on Cypress Lake. The sediments sank to great depth, but at the west end of Cypress Lake a split occurs in the fault, and from there westward there is a rise in the Knife Lake synclinorium segment with respect to the sediments northwest of the fault. These are now depressed possibly 1000 to 2000 feet as shown (Pl. 1, cross section 1-K). The amount of horizontal movement is very difficult to estimate; it may have been a short distance or a mile. It is believed that this fault does not stop at the west end of Knife Lake. It probably passes through Carp and Birch lakes and may even go through Moose Lake. Since these rocks are all sheared, the fault zone is very wide and indistinct here.

Canadian synclinal segment.—This segment, adjacent to the Knife Lake segment, lies entirely in Canada and is also confined between two faults. The total stratigraphic thickness of its sediments probably does not exceed 5000 feet. It has been studied less than the others, partly

on account of dense forest cover. Its movement with respect to the Knife Lake segment has already been discussed. On Emerald and Carp lakes it is displaced with respect to some sediments which rest directly on greenstone. Therefore, the Canadian synclinal segment must also have sunk with respect to the segment north of it. It would be entirely speculative to give anything but a very general idea for its vertical component of movement. What happens to this segment west of Carp Lake is impossible to state. It becomes very schistose and probably also very narrow in Birch Lake.

In the area north of this segment sediments lie on greenstone as already stated. They are composed of basal gray slates and graywackes which give little clue as to their structure, but, judging by the distribution of the greenstone outcrops, a narrow syncline pitching S. 50° W. may exist east of Emerald Lake in Canada north of sec. 24, T. 65 N., R. 7 W. Another with the same direction of pitch lies between Emerald and Carp lakes. This northernmost segment is faulted off at Carp Lake and does not extend west of it.

Knife Lake greenstone segment.—This segment extends from Swamp Lake in sec. 24, T. 66 N., R. 6 W., southwestward to Sucker Lake, sec. 6, T. 64 N., R. 8 W., where its identity is lost by shearing of the rocks. It is bounded by faults most or all of the distance. The name greenstone segment is thought appropriate because for a number of miles it consists almost entirely of greenstone. Near its northeast end granite pebble conglomerate overlies the greenstone. This is the former Grant (Gruner, 1929) conglomerate. It lies in a syncline of greenstone and grades northeastward into grit and graywacke and on Garrett Lake into well-banded slate. North of Opal Lake the sediments and greenstones are sheared so much in this segment that no interpretation of other structures is possible. A few outcrops of ellipsoidal greenstone were found unexpectedly along the western edge of the segment in NW¼ sec. 2, T. 65 N., R. 6 W. The structure is very complicated at this place, and a swamp makes closer investigation impossible. The downthrow to the west of the segment is measurable in thousands of feet. The little greenstone lens under discussion is east of the fault. Theoretically the greenstone should be about 1500 feet or more below the present surface. This greenstone could belong, therefore, to a younger greenstone of Knife Lake age lying between the slates or, more likely, it could have been brought into its present position by faulting.

The main greenstone belt on Knife Lake appears to be a double one, a northern and southern, separated by a conspicuous depression or valley in many places, which in secs. 17, T. 65 N., R. 6 W., and sec. 24, T. 65 N.,

R. 7 W., contains a few outcrops of slate. The southern belt contains many intrusions of quartz porphyry; the northern does not. As a matter of fact no porphyry was noticed west of sec. 19, T. 65 N., R. 7 W., in this segment. It is not possible to tell the tops from the bottoms of the flows by the shapes of the ellipsoids in any of the exposures.

At the south boundary of this segment, in sec. 10, T. 65 N., R. 6 W., the greenstone is in contact with a mass of intrusive felsitic and quartz porphyry rocks. Along this contact a fault separates the main mass of the white porphyry and slates from the greenstone. The greenstone was raised with respect to the sediments on the south a relatively small distance, perhaps 1000 to 2000 feet. It is difficult to find this fault for the following reasons: The fault zone is under water for considerable distances (Pl. 5, Fig. 2) and where it is on land the shear is inconspicuous for a displacement of over 1000 feet. It usually occurs at the contact of greenstone and sediments or of greenstone and white porphyry, and there recognition is relatively simple. In some places, however, it cuts through the slate leaving a little of the highly crumpled slate sticking to the greenstone. If on the other side of the fault the sediments show gradational bedding with their tops toward the greenstone, as is actually the case for a distance of 3 miles, it is easy to mistake the greenstone for a younger flow resting on the slates and graywackes.

In the E. ½ sec. 24, T. 65 N., R. 7 W., at the west end of the largest island, a fine contact between slate and greenstone may be seen. The slate shows good gradational bedding with tops away from the greenstone. There is no room for any fault at this place. The fault passes just south of this island. This contact between greenstone and slate shows that a basal conglomerate between the two does not need to exist, as was assumed by Clements (1903).

In sec. 23, T. 65 N., R. 7 W., the fault crosses over into the sediments with the "flinty slates" to the north and "well-banded Knife Lake slates and graywackes" to the south of it. The fault is defined by highly sheared slate outcrops or valleys and swamps. Vertical displacement is probably of very different magnitudes at different points along this fault and cannot be estimated. Many of the flinty slates are well banded, but gradational bedding is exceptional. There is nevertheless sufficient information available to show that the folds pitch toward the west in the south arm of Knife Lake. A fault may separate the greenstone from the slates here. A sheared iron carbonate zone at the edge of the greenstone on the north shore of this arm suggests such a fault. Otherwise sheared gray slates are directly in contact with the greenstone. The contact between the gray and flinty slates is concealed in the lake, and from here westward the larger portion of the Knife Lake basin is probably carved

from gray slates. The latter grade into phyllites on Birch, Sucker, and Newfound lakes, as do the flinty slates, but with this difference: The gray slates form green chlorite phyllites, and the flinty slates form light-brown sericitic phyllites. It is not possible to find definite fault zones in these highly altered rocks west of Sucker Lake. Displacement may have occurred in a large number of places, making the fault zones so wide that they merge into one another.

Spoon Lake segment.—This segment extends as a recognizable unit from the east end of South Knife Lake westward to Newfound Lake. The eastern portion consists of white felsite and quartz porphyry and conglomerate derived from these rocks. It is exceedingly difficult in many places to distinguish between the clastic and igneous rocks, especially since vegetation is dense. The older surveys mapped most of this material as slates and conglomerate. Bedding is practically absent except toward the western and northwestern margins of the conglomerate where it grades upward into finer arkosic beds containing lenses of conglomerate. These beds in turn grade into well-banded graywackes and slates which are especially well exposed on the shores in SE¼ sec. 17, T. 65 N., R. 6 W.

A narrow belt of ellipsoidal greenstone occurs in the white felsite in sec. 21, T. 65 N., R. 6 W. Its age relationship is not clear. One probably would be justified in believing the greenstone to be the older unless it is a dike.

The arkosic and graywacke beds which lie on the conglomerate have their tops toward the north and toward the greenstone where the tops are recognizable. They are almost in contact with the greenstone of the Knife Lake segment tops, and the idea of a large fault between them and the greenstone had been dismissed for some time as very unlikely. The greenstone was believed younger than the sediments; it is now believed that the greenstone is older.

West of the conglomerate area the folds pitch to the southwest as shown, for example, on the large island in sec. 19, T. 65 N., R. 6 W. From there to the east end of Spoon Lake the structure is especially complicated. North of Spoon Lake the sediments commonly show gradational bedding, but on the south side shearing has obliterated all indications of tops or bottoms of beds. West of Plum Lake a large synclinal structure may be followed westward to Ensign Lake where shearing becomes intense. Farther west the segment seems to pinch out near Newfound Lake. The total thickness of the sediments involved in these structures probably does not exceed 5000 feet.

Kekekabic Lake segment.—This segment has the greatest areal extent in the district. It begins at Lake Saganaga with a north-south strike,

gradually swings toward the southwest and west, and ends near Newfound Lake. Most of this distance it is bounded by faults except at and near Saganaga Lake. Here, on Cache Bay, the well-known granite pebble and boulder conglomerate lies directly on the Saganaga granite. The conglomerate grades into arkosites and graywackes toward the west and south within a short distance. At Swamp Lake only relatively few pebbles and no boulders are found in the graywacke. On Alpine Lake the conglomerate appears again in similar relation to the granite, but with only minor amounts of granite pebbles as compared with pebbles of greenstone. This conglomerate grades into graywacke and slates northwestward, but another conglomerate abruptly appears at Opal and Crooked lakes and farther north. The latter is a very prominent belt and locally extremely coarse. Its western limit is the fault contact with the "Knife Lake greenstone segment." The coarseness of this conglomerate and the abruptness with which it was laid on the graywacke in many places is astonishing. Round granite boulders more than a foot in diameter may be found almost directly on the fine-grained sediments.

The conglomerate which occurs on Alpine Lake continues as such southwestward and develops into the "Ogishke granite pebble conglomerate." It reaches a thickness of 3000 feet north of Ogishkemuncie Lake. Beyond Zeta Lake it thins rapidly and grades along the strike into grits and graywackes. According to Stark and Sleight (1939) it is underlain unconformably by a belt of slate and graywacke named by them "Dike Lake slates." Arguments for and against such an unconformity have been given.

Greenstone conglomerate, member(3), is found south of and evidently under these sediments. It is in fault contact with unclassified slates which lie on the greenstone of Twin Peaks and Gabimichigami Mountain. The conglomerate, however, is in direct contact with greenstone in sec. 5, T. 64 N., R. 6 W.

The bedding is very poorly developed in the greenstone conglomerates, and it is very rare to find a strike direction in this densely wooded area. The meager evidence points to a relatively flat-lying conglomerate and agglomerate through which the underlying andesite porphyry or greenstone floor seems to project in two places, in the SW¼ sec. 27, T. 65 N., R. 6 W., on the south shore of Ogishkemuncie Lake, and in the NW¼ SW¼ sec. 26, T. 65 N., R. 6 W.

The sediments of the Amoeba Lake member overlying the Ogishke granite pebble conglomerate are several thousand feet thick, and their tops are toward the northwest east of Eddy Lake. West of the lake they surround a mass of hornblende andesite porphyry which either is a volcanic neck or, more likely, a part of a flow which later was infolded.

The evidence that this rock is younger than the surrounding sediments is clear, for their tops are toward the porphyry in all places examined. It seems, however, that the porphyry truncates or bevels the tuffs and slates in a number of places suggesting an irregular land surface for a base.

The Kekekabic granite stock which was studied in detail by Stark (1927) is a prominent feature of this segment. It fills a portion of a complex synclinorium which surrounds and holds Kekekabic Lake. It appears as if the stock had made room for itself partly by crowding the sediments southeast and south of it, and partly by stoping its way upward. Whether it should be called a satellite of the Snowbank stock, as Stark has done, is not certain. The writer is convinced that the roof of a batholith probably of the Basswood granite is not so very far below the present surface, between the Snowbank and Kekekabic stocks, because the rocks in this region show more metamorphism than they do east of Kekekabic Lake. The greater metamorphism might be partly ascribed to the nearness of the Duluth gabbro. A small stocklike mass of syenite about 75 paces wide outcrops at about the NW. corner of sec. 8, T. 64 N., R. 7 W., and veins containing quartz, potash, feldspar, and epidote are more common in this area.

The gabbro to the south largely covers the structures which connect the sediments of the Twin Peaks area with those southwest of Kekekabic Lake. The fault, which is shown as reaching the gabbro in the NE¼ of sec. 9, T. 64 N., R. 7 W., probably continues eastward under the gabbro and may possibly connect with the one shown northeast of Twin Peaks. The sediments of the segment west of Kekekabic Lake narrow rapidly and consist largely of conglomerates and agglomerates.

The movement of the segment relative to adjoining ones seems to be downward largely (Pl. 1, cross section G-H). On Eddy Lake the throw may amount to 10,000 feet where member (9) is in contact with quartz porphyry. West of Kekekabic Lake there is no simple way of ascertaining in which direction the segment moved.

The conditions which exist in connection with sedimentation in this segment require special attention. Just west of Alpine Lake, in the E½ sec. 7, T. 65 N., R. 5 W., conglomerate overlies greenstone and granite. This conglomerate has been sometimes named Jasper pebble conglomerate, and its relationship to the granite was described by Clements (1903, p. 272). Stark and Sleight (1939, p. 1034), referred to it as West Gull Lake conglomerate. Since it overlies the Saganaga granite its age seems fixed. Granite as inliers is found surrounded by the sediments (and greenstone) as far as 2000 feet west of the main mass. The conglomerate dips steeply away from the granite inlier (Pl. 1, cross section C-D) as far as could be observed in the few available outcrops. How such steep dips

are possible around a relatively small igneous mass is not easy to explain. Grout (1936, p. 268), in discussing the structure of the Saganaga granite, concludes that the whole granite mass has been turned on its side which requires an angular movement of about 70° about a N.-S. axis miles to the east of the conglomerate-granite contact. One reason for such an assumption is that the dip of the sediments where they are in contact with the granite is commonly 65° to 70°. No shearing seems to have occurred along the exposed contact, and therefore the granite and the adjacent sediments must have moved as a unit.

In the present study certain facts were discovered by the writer which seem to make the partial overturning of the Saganaga batholith problematic: (1) The contact between granite and sediments is not a simple surface with only minor irregularities on it, as it should be, but is highly complex. In sec. 30, T. 66 N., R. 5 W., there is a large plunging fold which extends into the granite in such a manner that the sediments of one limb are 2000 feet farther east than could be explained by the turning. On the northwest limb of this syncline the sediments actually dip toward the main mass of the batholith. (2) The aforementioned inliers of granite surrounded by conglomerate show that the contact is very complex. A restoration of the contact to the original position assumed by Grout would submerge certain portions of the sediments in the older granite. (3) A study of the southern contact of the granite shows that the granite, together with the surrounding greenstone, acted as a kind of buttress to the sediments on this side just as it did on the west. In other words, the conglomerates are also on edge but strike nearly at right angles to those on the west side of the granite.

It is not proposed to contend that a granite mass of the dimensions of that on Lake Saganaga cannot turn over. It is possible, however, to explain otherwise the steep dip of sediments on the flanks of earlier crystalline rocks which acted as buttresses. The idea of buttresses in connection with folding is not new, but it does not seem to have been associated with the floor underlying a synclinorium and the differential resistance which the buttresses might encounter in their movements. The stages in the making of a synclinorium with such a floor may be described and illustrated (Fig. 5) as follows: The floor and whole basin of deposition as before deformation are assumed to be composed of crystalline rock of much greater strength and competence than that of the sediments. For simplicity's sake assume that it is almost uniform like a granite. Assume also that a very thick cover of other rocks, largely sediments, rests on the synclinal structure, including the buttresses, and provides the load under which intense folding takes place. This cover is in addition to

the sediments shown in the diagram and is, of course, involved in the processes of folding.

As gradual pressure is applied from opposite sides, as indicated by the arrows, the resistance encountered is a function of a large number of

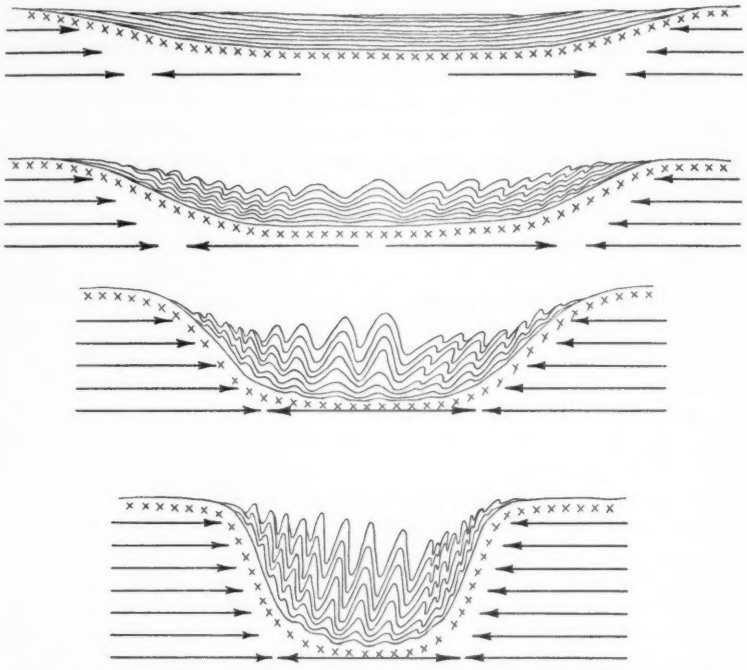

FIGURE 5.—*Stages in development of a closely folded synclinorium which is underlain by a competent floor*

Lengths of arrows are not proportional to magnitudes of force. The rocks overlying those illustrated and which are largely in the zone of fractures have been omitted in the drawing for simplicity. Depth of synclinorium is exaggerated in proportion to its width.

factors. Chief among them should be the assumed greater strength and competence of the rock comprising the floor as compared to that of the sediments to be folded. It will resist compression as shown by arrows pointing outward. Therefore, gradual steepening of the buttresses must occur because resistance at higher levels is less. This steepening depends upon slow flow of the buttress rock. The floor rock can move too, of course, but it is more confined, and its direction of flow will depend largely upon load adjustments. It could move upward if the sediments were

lighter than surrounding rock units. More likely the floor would move downward because shortening of the sediments horizontally increases the load vertically. The sediments will be folded during this movement as illustrated. The synclinorium which gradually develops is different in some respects from those commonly found illustrated in textbooks. The amplitudes of the folds near the floor are small, but they increase rapidly as the vertical distance increases. Most of the thickening of the beds will be at the noses of the anticlines, because there the relative resistance to upward escape is less than in the troughs. That actual observations of these conditions have not been reported is due to the difficulty of finding exposures of very great vertical extent in which the floor of the synclinorium is also visible.

The sediments finally will be steeply dipping where they are in contact with the buttresses. The chief objection raised in the case of the Saganaga granite conglomerate will be that the granite boulders show no noticeable flow lines related to this folding. The absence of flow lines in the granite boulders would be just as difficult to explain, however, if the granite mass had been turned over. The pressure to which they would have been subjected would hardly have been any smaller. An argument in favor of the buttress hypothesis is the fact that the lamprophyre dikes in the Saganaga granite (Grout, 1929; 1936) which have been described in detail by Sundeen (1936) are much more nearly vertical than horizontal. If the granite mass had been turned over the dikes at the time of intrusion would have been nearly horizontal, an attitude not in conflict with modern petrologic thought, but rarely found in the field.

Gabimichigami Lake segment.—This segment extends from Twin Peaks to Alpine (formerly called West Gull) Lake, in a northeasterly direction, and to the range line between R. 5 W. and R. 4 W. toward the east. A part of the segment might be considered a definite unit because its structural trend is quite different from those discussed so far. It is as a whole about S. 60°-70° E. Much of the geology of the segment is still obscure, but the Agamok syncline named by Sleight [2] after the lake by this name has been mapped in detail by the author. The syncline is cut off toward the northwest by the fault which separates it from the Kekekabic segment. This fault coincides with a broad shear zone in which iron-bearing carbonate (Agawa of Clements, 1903, p. 327) has replaced a considerable width of sediments. The shear zone can be followed readily northeastward as far as Townline Lake, but it is not certain whether it continues beyond toward Alpine Lake. Southwestward the fault zone may be traced as far as Twin Peaks. For the last 2 miles it separates greenstone

[2] Ph.D. Thesis, Northwestern University.

conglomerate and andesite porphyry conglomerates on the northwest from slates and graywackes on the southeast. The latter are basal gray slates and graywackes which lie directly on greenstone. The slates skirt the greenstone around its northernmost point in sec. 35, T. 65 N., R. 6 W., and then turn sharply southeastward to form the southwest limb of the Agamok syncline.

The Agamok synclinorium and the other sediments farther east seem to be rather shallow. Observations are difficult because of much vegetation but, where they can be made, the dips are as low as 25° on the southwest limb. Farther east it appears that all the folds are very shallow and that they were greatly influenced by the behavior of the "floor" upon which they rest. It is evident, as was partly brought out in figure 5, that the shapes of the folds which are close to the floor of a synclinorium should reflect the competency and present "topography" of this floor. Shallow folds and confusion of them with respect to strike and dip should indicate nearness to an irregular floor. In the folds situated relatively far above this floor, much more regularity should prevail with respect to their general strike and distribution in plan view. One might even go so far as to make the lack of regularity of folds a criterion of the closeness of the "basement complex," the lithological composition of which is of an entirely different character as compared with the folded sediments.

Only by such reasoning is it possible to explain the confused distribution of the sediments in the Gabimichigami segment. Otherwise it is necessary to assume a thickness of greenstone conglomerate and andesite porphyry conglomerate in the neighborhood of 10,000 feet in sec. 21, 22, 28, 27, and 26, at the eastern end of the segment. The occasional visible dips in some of the less coarsely grained beds are steep, and the tops are everywhere toward the northeast in the few places where they can be recognized. These few dips and gradations could give one an entirely erroneous picture. If the conglomerate represents a number of shallow asymmetric folds or mere wrinkles, the steep limbs could be plotted more nearly correctly than the moderately dipping ones because the surface is largely flat, and flat dips are not noticeable. The lithology of this conglomerate including large portions of agglomerate is so uniform that unless good outcrops are available the rock might be mistaken for massive porphyry in a number of places, especially since there are undoubted porphyry areas closely associated with the sediments. It is not at all certain that the porphyries should be mapped as Ely greenstone or even as Archean, for in sec. 21, T. 65 N., R. 5 W., they cut ellipsoidal greenstone.

Much time was spent trying to find some evidence as to the age of the andesite porphyry conglomerate. Is it possibly metamorphosed by

the Saganaga granite? Occasionally near the granite in secs. 21 and 22 it seemed as if the matrix and the pebbles were converted to a more coarsely hornblendic rock than they are at a greater distance from the granite. No decision could be reached, however, and though the material looks very much like other andesite agglomerates and conglomerates at Kekekabic Lake and other places, the fragments of which are probably not derived from Keewatin greenstone, the rock has been called a greenstone conglomerate provisionally.

Great difficulty of interpretation was experienced in sec. 25, T. 65 N., R. 6 W., and sec. 30, T. 65 N., R. 5 W., where the forest is dense and ellipsoidal greenstone outcrops in a number of small patches. The greenstone seems to be overlain directly by slate and graywacke, except in sec. 25, where a belt of greenstone, though ellipsoidal, looks like a dike. The slates and greenstone seem to dip into it from both sides at angles of 80°. Gradational bedding is not good enough to justify a decision. It appears, nevertheless, as if the tops of the slates were toward the greenstone except in one place. There is no shearing on either side of the belt, from the absence of which one might also conclude that the rock is an intrusive.

Ensign Lake segment.—Most of the segment by this name was mapped by George Gibson. It is triangular in shape. Ensign Lake fills a part of its western half. Faults on the north and southwest separate it from other segments, while the gabbro delimits it toward the southeast. The part near the gabbro forms a number of isoclinal folds of east-west strike. Squeezing becomes more severe toward the west and is most pronounced on the south shore of Ensign Lake. A transverse fault, or series of faults, in Boot Lake splits and fans out northward to Ensign Lake. Shearing is intense at this place. The strike of the sediments south of Bass Lake is about N. 60° W., which is a considerable departure from the east-west strike farther north. Since a large swamp is found along the line where the strikes change, a fault zone may be hidden there. A hornblendite mass, resembling in structure a sill, outcrops between Ensign and Bass lakes and intrudes the slates and tuffs along one of the synclinal axes of the synclinorium on Ensign Lake. The southern apex of the segment around Disappointment Mountain is an anticlinal area with a core of ellipsoidal greenstone which is surrounded by greenstone conglomerate. A great thickness of agglomerate and tuffs lies on this to the north. Since no bedding is visible in these sediments detailed structures cannot be recognized. It is, however, highly probable that a fault which exists farther west in sec. 28, T. 64 N., R. 8 W., extends eastward and displaces the greenstone conglomerate with respect to the agglomerates. The south-

ern block was raised with respect to the sediments on the north. These, in turn, seem to have been elevated a very considerable vertical distance with respect to the adjoining Snowbank segment.

Snowbank Lake segment.—This segment, mapped by C. E. Dutton, G. R. Gibson, F. F. Grout, and J. W. Gruner, lies near Moose and Snowbank lakes. It contains the Snowbank granite stock which probably was the cause of the peculiar distribution of some, if not of most, of the folds and faults near it. The strikes of the sediments of the larger folds to the northeast and southwest of Snowbank Lake are definitely southeast with a pitch in the same direction, but on Moose Lake the strikes are east or northeast, and extreme shearing is found on all shores of Moose Lake. One of the best defined structures of the segment is the large syncline northeast of Snowbank Lake. Its stratigraphy has already been discussed under the members (16), (17), and (18). The setting suggests that its sediments are stratigraphically thousands of feet above the basal beds. They may correspond to the highest ones exposed near Rabbit Lake in the segment of the Knife Lake synclinorium. Clements and his associates (1903) mapped this syncline as anticlinal because they mistook the conglomerates for a "basal" conglomerate.

The southern third of the syncline, which is faulted off from the rest, has an enormous thickness of sediments on its west limb, while it is much thinner on the east limb where the sediments rest on greenstone. There are two plausible explanations for this condition: (1) The NW.-SE. fault which reaches the north bay of Disappointment Lake may continue southward to the gabbro contact, and the block east of this fault has been raised; or (2) a considerable unconformity may exist between the greenstone conglomerate, member (3), and the slate pebble conglomerate (18), east of Disappointment Lake.

The large accumulation of agglomerate and tuff in this segment may be of the same age as those on Kekekabic Lake. Since the beds are almost devoid of all visible structure it is impossible to fit them into the general structure with any satisfaction. It is possible that the feldspar porphyries which occur as "blow-outs" and as other intrusive bodies in them are genetically connected with the agglomerates.

DISCUSSION OF STRUCTURAL GEOLOGY

After having finished a complicated structural problem like the present one, one might well ask what the investigation produced that will be of general application in the study of highly folded sediments of pre-Cambrian shield areas. The Knife Lake district is representative of large portions of the Canadian Shield. It contains metamorphic rocks

which still permit the identification of certain primary sedimentary features such that the recognition of tops and bottoms of beds is possible. It is evident from inspection of the maps that without them it would have been impossible to interpret any but the simplest structures.

The survey by Clements and his associates (1903) who did not examine these primary structures differs, therefore, very considerably from the present one. Most "greenstones" were considered Keewatin in age, and most conglomerates were considered "basal" conglomerates.

It cannot be too strongly emphasized that in nonmarine deposits, such as those of the Knife Lake series, a conglomerate lens, even of large dimensions, does not indicate a considerable break in sedimentation immediately preceding the deposition of conglomerate. It represents changes in deposition which may have been extremely rapid. That the conglomerates were laid on fine-grained beds without cutting more into them presupposes a hardened and somewhat consolidated condition for the fine-grained beds. On this basis one could argue that there must have been a considerable time interval between deposition of the beds under the conglomerate and the conglomerate itself. Are these intervals measured in thousands or millions of years? That it cannot have been the latter span is shown by the scarcity of angular unconformities. None was discovered in the Knife Lake series itself, except for the one mentioned by Stark and Sleight (1939).

The observation that conglomerates grade into agglomerates along the strike is not new, but the writer knows of no area where this gradation is more striking. To produce such relatively rapid gradation or transition necessitates vigorous volcanic activity and rapid physiographic changes.

The great similarity of certain andesite porphyry clastics, though their fragments probably came from two entirely different series of andesites, as, for example, member (4) and portions of (11), is very striking. It demonstrates very forcefully that similarity, almost lithological identity, of fragments is not an indication that the fragments are derived from the same mass. Certain conglomerate-agglomerate sediments in the district are, therefore, of doubtful age and position in the series though lithologically they are the same.

It has been assumed by many that a conglomerate on an ellipsoidal greenstone is evidence of a long erosion interval. At first it was thought that slates could not be deposited directly on greenstone but that conglomerate, though thin, must lie between the two. Later when slates were found directly on the greenstones, long erosion intervals were also postulated. There is, however, nothing in these processes of deposition which demands such an interval. If the ellipsoidal basalts are largely subaqueous flows, there is no reason to believe the sedimentation was interrupted for any great length of time after the eruption of the lavas.

If it can be shown, however, that large masses of an entirely different igneous rock were injected into the greenstones before deposition began, then erosion probably was active in the interim. This can be demonstrated for a large part of the district where white porphyries and the Saganaga granite inject the greenstone. On the other hand, there must be places where the sediments followed the greenstones (basalt flows) immediately, and both are now exposed. In them no criterion is known at present to differentiate between the two ages. Without Laurentian intrusives it becomes impossible, therefore, to estimate the time interval between greenstone and sediments deposited on it.

One of the most puzzling problems in closely folded regions is the depths to which folds reach in proportion to their widths. If the pitch is approximately known, it is, of course, possible to project the folds to the place where a reversal of pitch occurs. This would be the maximum depth. The question resolves itself to this, then—can the average pitch of a set of folds or of a synclinorium be found?

It was pointed out that the pitches of the minor folds actually observed are rather steep, many of them 60°. Others have much lower angles, some as little as 10°. Owing to the flatness of the peneplaned region, flat pitches can be easily overlooked, and steep ones are readily observed. Cliffs should be the best places for measuring flat pitches. This is actually the case, but unfortunately many cliffs in the area are parallel to the strike of the beds in which attitude the pitch of a fold is difficult to observe.

It was possible in the present study from the data collected to compute the approximate average pitch of the Knife Lake synclinorium as 15 to 25°. The conclusions are partly based on the observation that the sediments have not been much thinned on the limbs by metamorphism, for many primary sedimentary structures are still intact. This, in connection with the areal distribution of the folds, led to the belief that the folds are not any deeper than shown (Pl. 1, cross sections C-H). The depth of folding in other segments of the Knife Lake district is of unknown magnitude, but it may be expected that it would not exceed much the Knife Lake synclinorium, the sediments of which are 2 to 3 miles thick stratigraphically and among the thickest found in the region.

The discovery of faults depends largely on the amount of detailed work done. Since most of the faults seem to be longitudinal or strike faults, they are found only after realization that certain structures do not "make any sense" when fitted together. A checkup in the field will usually show depressions in these places. There must be still other faults, some even with fairly large displacement, which were not discovered. The probable faults through and parallel to Moose, Newfound, Sucker, and

Birch lakes have already been mentioned. The shear zones are so broad that displacement probably is not confined to a definite plane. The area occupied by Sucker and Newfound lakes seems to be the focus of more than one fault and structure, synclinal or anticlinal, as can be seen on the map. It is at this place that the Basswood granite and Snowbank Lake stock approach each other to within 2 miles (Clements, 1903, Atlas). The particularly intense shearing and metamorphism at this locality may be largely a result of motion between two resistant buttresses.

The trends of the structures in the district result from the action of buttresses and the intimately connected "basement complex." No better example can be found than the Saganaga granite and associated greenstone mass which was instrumental in producing northward-striking folds to the west of it and southeastward-trending structures south of it. The shallowness of the "basement complex" of greenstone between Michigami Mountain and Jasper Lake influenced the structures markedly. Their peculiar and confused pattern must be ascribed to the irregularities in the underlying greenstone surface.

This surface, of course, was subjected to some of the same warping and folding as the sediments above, but the greenstone flows were not thrown into tight isoclinal folds. This impression seems to have been conveyed by Clements (1903, p. 135), when he writes:

> ". . . we find that the greenstones have been intricately folded, the folds have in many instances been carefully traced, and it has been found that in general the greenstone has been folded into a great synclinorium."

The greenstones are unquestionably very thick. Many are coarse-grained, probably intrusive. The material as a whole is fairly uniform and does not consist of competent and incompetent layers as do sediments. Therefore, the greenstones behave quite differently from sediments. They can be flexed, sheared, tipped on edge, or will flow in the zone of flowage, but the author does not believe that they occur as isoclinal or close folds unless they happen to be individual relatively thin basalt flows between thick sediments. More or less proof for this statement is the fact that the felsite and porphyry dikes of Laurentian age in the greenstones are mostly vertical and straight and show few if any defects of deformation due to folding of the greenstones. It might be argued that the greenstones were folded before Laurentian intrusion. This obviously would not explain why they were not folded again when the most severe period of folding of sediments occurred at the end of Knife Lake time.

GEOLOGIC HISTORY

The surface upon which the Keewatin greenstones were poured out has not been found in the Vermilion district. Therefore, the volcanic

activity with which the greenstones are genetically connected is the first recorded event. Sedimentation was active at the same time, though it is impossible to point to any particular slate on the greenstones as Archean in age. Soudan iron formation was deposited at about the same period, but there is no proof that any lenses of iron formation in the map area are Soudan and not Knife Lake in age since they are at the contact of greenstones and slates and not entirely surrounded by greenstone.

Intrusions of Laurentian granitic magmas at this time resulted in the Saganaga batholith and numerous white felsitic and porphyritic dikes and stocks. It must be assumed that the whole region at this time was mountainous. Gradually the country was eroded, and sediments were deposited on the greenstones. The sediments were largely, if not entirely, continental in character. Volcanic activity was widespread during certain periods. Deposition must have been rapid, judging by the coarse grain of the clastics and the abundance of tuffaceous material. Andesitic magmas contributed most of the pyroclastics. During this time enough iron was added to the sea to produce small lenses of iron formation, though some of these were probably replacements connected with igneous activity. At no time was any large amount of iron formation precipitated that can be found today. No ellipsoidal greenstone flows formed during Knife Lake time. The closest approach is a mass of hornblende andesite porphyry which, however, is not ellipsoidal and is different in appearance. Most of the pyroclastics are of the same composition as this porphyry. There exist a few small intrusions of a badly altered feldspar porphyry which probably were injected a little later than the andesitic magma.

Physiographic conditions and topography changed so rapidly during Knife Lake time that lenses of coarse conglomerate, often of great thickness, were deposited throughout this period. In some chert pebbles of these conglomerates fossil algae are still preserved.

Orogenic movements on a tremendous scale some time later produced close folding of the sediments and was accompanied by the Algoman intrusions. Most of these were granitic in composition, but a small one south of Ensign Lake was a hornblendite. The latter preceded the Snowbank syenite stock. A very long interval of erosion followed during which time the Algoman mountains were peneplaned. The Animikie sediments were laid on the truncated roots of them and in this district include only a very narrow band of Gunflint formation and Rove slate.

Keweenawan diastrophism produced some tilting of the older formations toward the south. Duluth gabbro as an enormously thick sill was pushed between the Animikian sediments or followed the contact between

the older rocks and Keweenawan flows. Numerous diabase dikes and sills invaded all the older rocks.

From then until today erosion has been active in the region. There exists, at least, no record of deposition of Paleozoic or younger rocks. The continental glaciers of the Pleistocene were among the most active agencies of erosion.

CONCLUSIONS

A detailed structural geology study was made of the eastern half of the Vermilion district of Minnesota. This area was selected because: (1) The exposures are very numerous, (2) former studies had shown that most series of the geologic column as high as the Keweenawan are represented, and (3) the rocks are so little metamorphosed that the finished investigation would admit of fairly certain conclusions. The results may be summarized as follows:

All ellipsoidal greenstones are of Keewatin age. One or two later basic dikes seem to confuse the issue because they also show ellipsoids. No evidence was found that these greenstones were ever folded into tight isoclinal structures though they were warped and tilted. Most "anticlinal" structures of the greenstones are accentuated by faulting. No Coutchiching formation was found.

The Knife Lake series is continental in origin and comprises the rocks formerly called the Ogishke conglomerate, Agawa iron formation, and Knife Lake slates. Many different members occur in it. These cannot be separated into the three former divisions however. No basal conglomerate in the sense in which the name Ogishke conglomerate was used exists. No distinct Agawa formation was found. The conglomerates may appear at any horizon in the Knife Lake series and small lenses of iron formation are not restricted to any particular horizon. Some of these lenses seem to be replacements of sediments. Thick deposits of pyroclastics from very coarse agglomerates to the finest tuffs are common. The agglomerates commonly grade into conglomerates along the strike. The agglomerates as well as one mass of igneous rock, probably a flow, are all andesitic in composition. No major unconformities were observed in the Knife Lake series. The almost complete absence of truncation even on a minor scale is remarkable. Very coarse conglomerates lie directly and conformably as far as appearances are concerned, on fine-grained sediments.

The Knife Lake series and older rocks are traversed by longitudinal faults of great lengths. There are also some shorter transverse faults. The area is cut into segments by these faults. The structure of each segment can be deciphered, but the correlation of adjoining segments

remains highly speculative. The thicknesses of the Knife Lake series vary from segment to segment, but the total thickness is probably not over 3 miles. The mean pitch of the largest synclinorium was computed to be 15 to 25 degrees. It is thought that all of them have average pitches of similar magnitude. The average or mean pitch may deviate much from local pitches. The steeper pitches are more commonly noticed. Another observation, which is not new, but may prove of value, is that drag folds are much more numerous and well developed near the noses and troughs of large close folds than on their limbs.

The contact between the Saganaga granite and the younger Knife Lake series which rests on it was investigated especially. In this connection a theory is advanced to account for the steep dips of such contacts of igneous rocks and younger sediments. No doubt these igneous masses act as competent "basement complex" and form buttresses against which sediments are folded. It was also observed that the regularity or irregularity in the strikes of the folds is an indication of the distance of them above the basement complex, those of greater regularity being considerably above it.

The Kekekabic Algoman granite is intruded in a synclinorium of the Knife Lake series. The Snowbank stock cannot be associated with any single structure though it is unquestionably responsible for the distribution of the folds around it. It is thought that these two intrusives are connected at not too great a depth because a similar mass, though very much smaller, crops out between them.

In closing it must be admitted that much of the structure remains hidden. Especially discouraging is the fact that the individual segments could not be correlated. It is encouraging, however, that a number of important questions were answered which should benefit the students of pre-Cambrian shield regions.

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University of Minnesota, Minneapolis, Minn.

Manuscript received by the Secretary of the Society, July 8, 1940.

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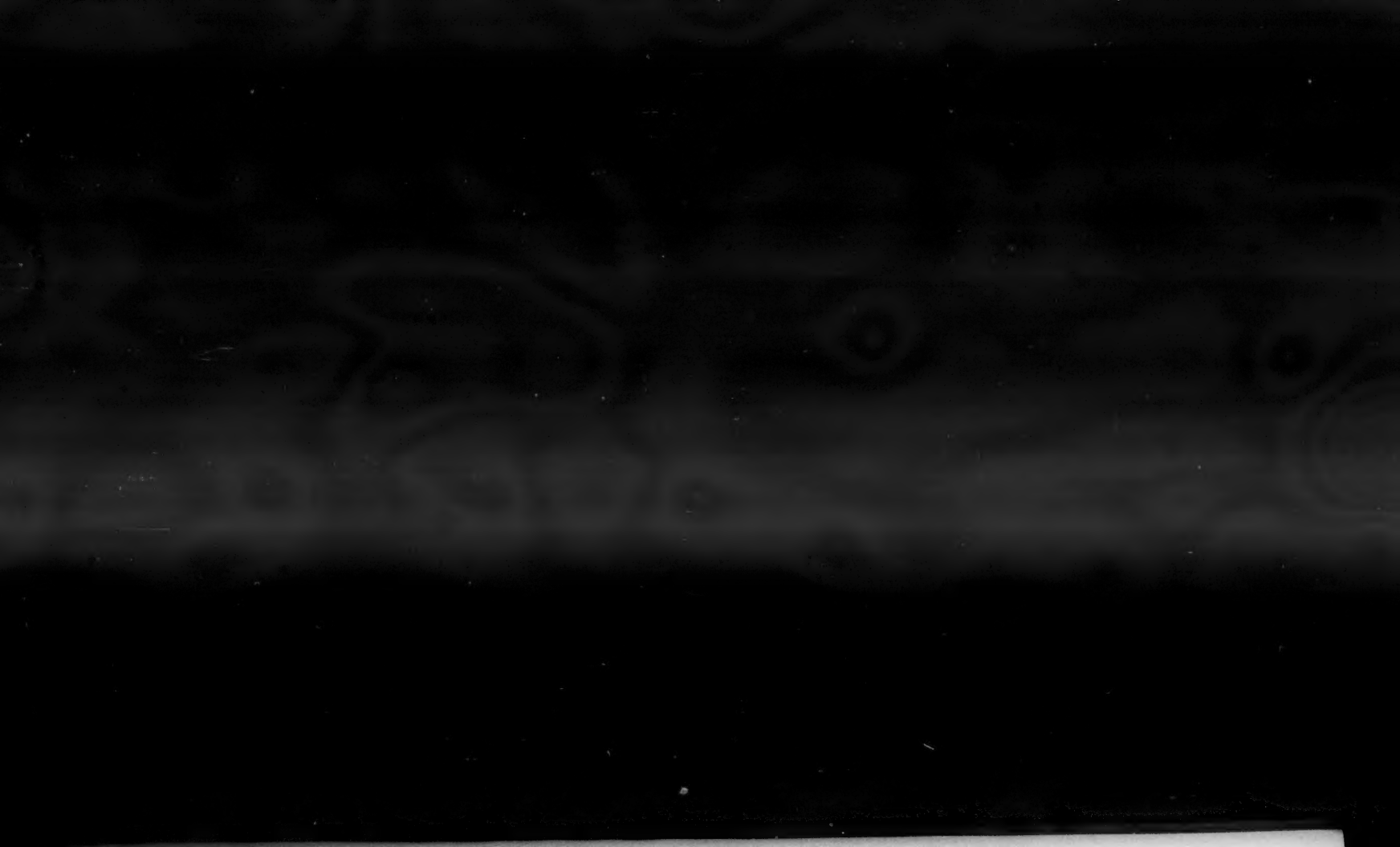
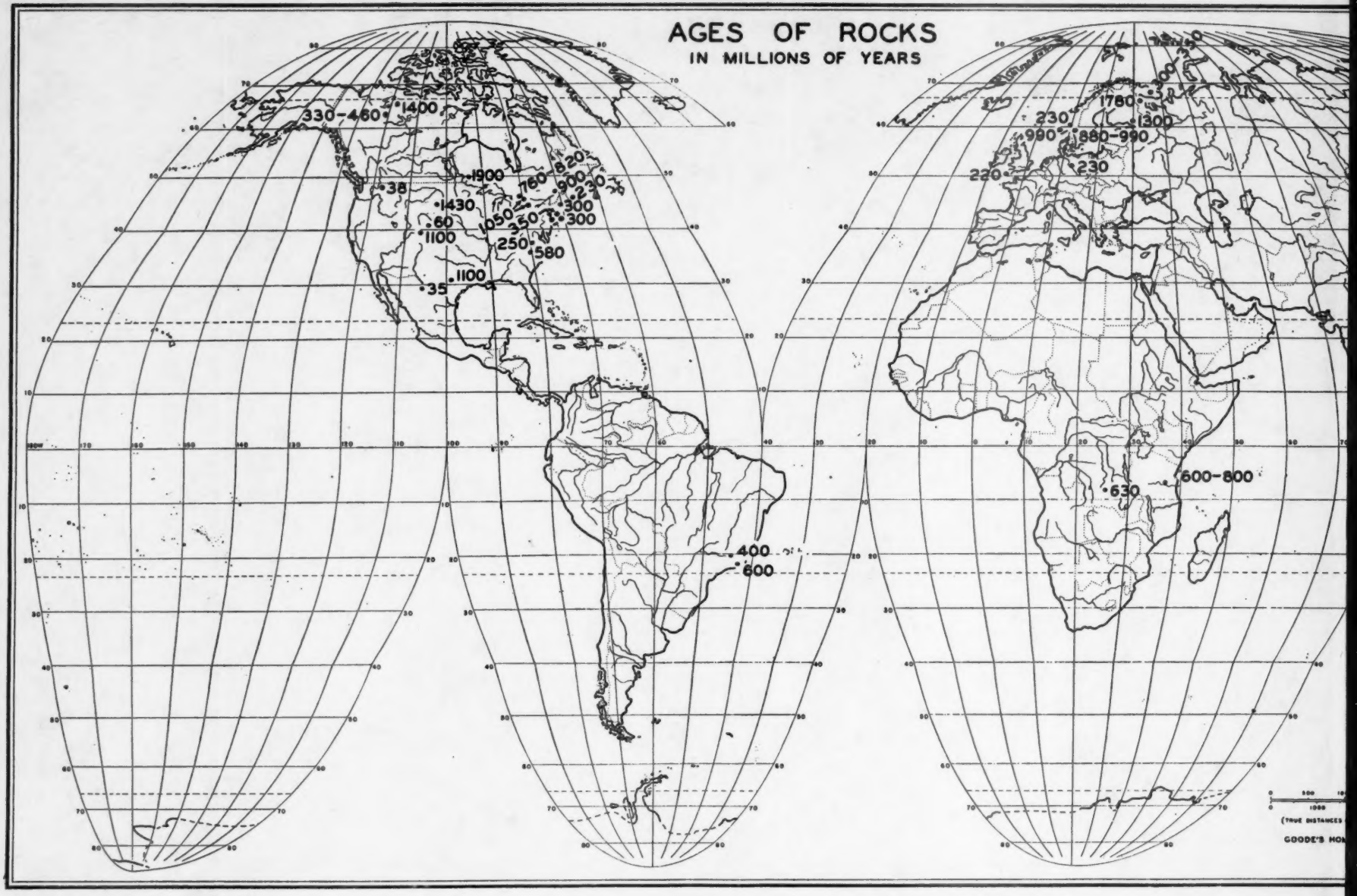
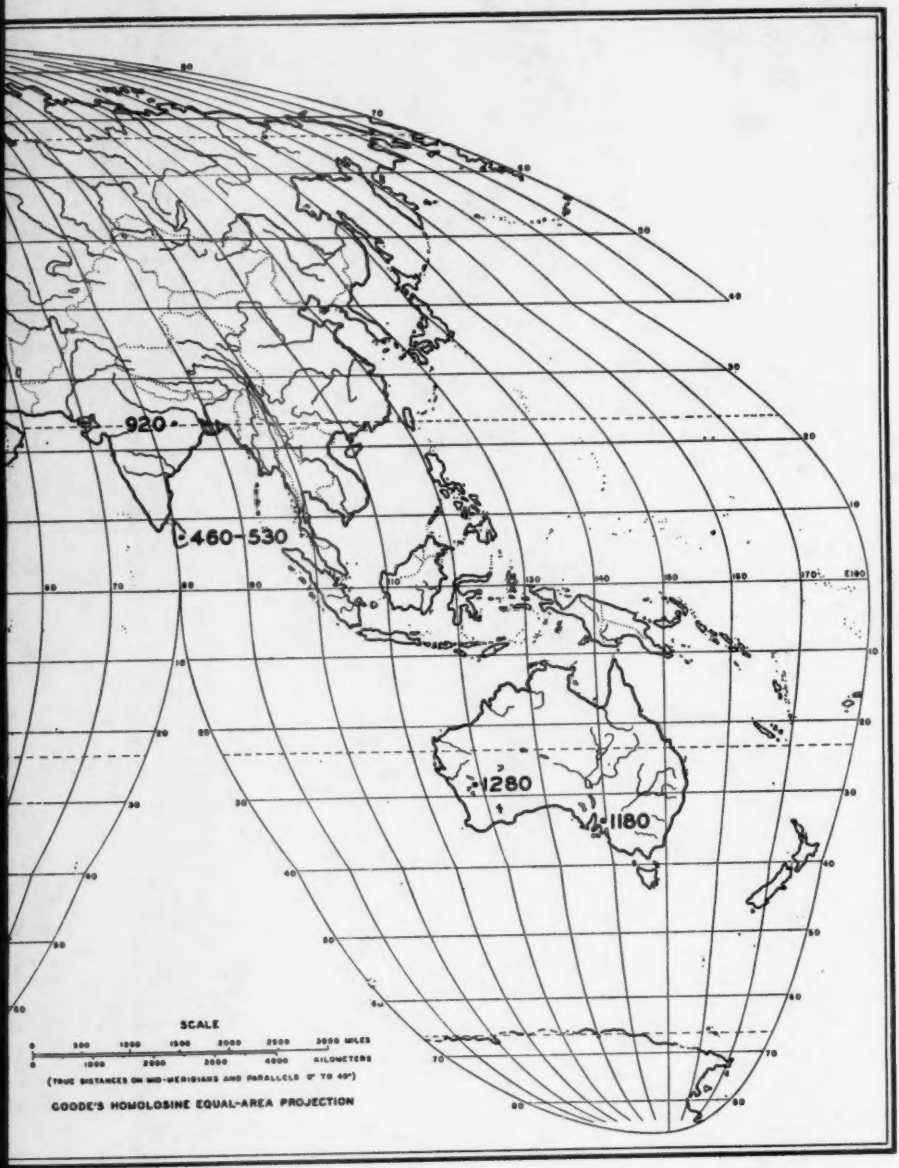




AGES OF ERUPTIVE ROCKS
In Millions of Years


920
460-530
1280
1180
SCALE
0 500 1000 1500 2000 2500 3000 MILES
0 1000 2000 3000 4000 KILOMETERS
(TRUE DISTANCES ON MID-MERIDIANS AND PARALLELS 0° TO 40°)
GOODE'S HOMOLOSINE EQUAL-AREA PROJECTION

BULLETIN OF THE GEOLOGICAL SOCIETY OF AMERICA
VOL. 52, PP. 1643-1684, 2 PLS., 9 FIGS. OCTOBER 1, 1941

ERUPTIVITY AND MOUNTAIN BUILDING

BY BAILEY WILLIS AND ROBIN WILLIS

CONTENTS

	Page
Abstract	1644
The problem	1644
Terrestrial eruptivity	1645
Crustal mosaic	1648
Deep-seated foundations	1650
Mechanics of crustal stability and failure	1653
General statement	1653
Static solid crust	1653
Changes during melting	1656
Stress relationships of a molten mass	1657
Development of an asthenolith	1660
Melting stage	1660
Molten stage	1662
Intrusion and flowage	1662
Illustrations	1663
Metamorphic action	1664
Effective radius	1673
Development of an orogeny	1674
Japan	1677
Japanese area in general	1677
Conclusion	1681
Works to which reference is made	1681

ILLUSTRATIONS

Figure		Page
1.	Hypothetical relations of strength to load in earth's crust under normal conditions	1654
2.	Elastic support of local loads	1655
3.	Development of stresses in and around a molten mass	1659
4.	Potential shearing planes in cubic crystal; two dimensions	1666
5.	Potential shearing planes in cubic crystal; three dimensions	1667
6.	Effect of shear on balance of atomic attractions and repulsions in crystal lattice in 100 or 010 plane	1668
7.	Effect of shear on balance of atomic attractions in crystal lattice on 110 plane	1670
8.	Distribution of granites in Japanese Archipelago	1679
9.	Hypothetical section through the orogenic mechanism of southern Japan	1680

Plate		Facing page
1.	Ages of eruptive rocks, in millions of years	1643
2.	Tectonic map of the Japanese Archipelago	1678

ABSTRACT

The following paper presents the concept that the terrestrial globe has hot spots where melting follows upon gradual heating by radioactive energy, and that in connection with such spots orogenic disturbances may develop: it is suggested that the growth of a molten body produces uplift; uplift results in unbalanced load; unbalanced load tends to cause lateral creep; heat from the molten body initiates expansion in the cover and also reduces strength of rock; creep becomes plastic flow by intimate, low-angle shearing; when shearing progresses to displacements on structure planes of crystal lattices atoms are forced out of balanced positions and jump into new ones; crystals are thus elongated and the crystalline rock mass is expanded accordingly; a very powerful thrust is thus set up and the opposing rock mass is sheared on a level at or near the top of the molten body; the magma transmits hydrostatically the pressure exerted upon it by the wall at the deep level of its bottom; that relatively great pressure causes it to intrude the major shear at the base of the expanding segment and to lubricate it; the dynamic elongation of the cover and the lifting power of the magma combine to thrust the segment forward and upward and it appears at the surface as a mountain uplift, characterized by sheared and folded rocks in association with intrusives. Emphasis is laid upon the fact that the rate of heat generation is extremely slow and the cycle of an orogeny should comprise the stages of initiation, gestation, upthrust, and decadence, *i.e.*, the time lapse of millions of years from peneplain to peneplain, but not the succeeding period of stability.

THE PROBLEM

The following discussion deals with the problem presented by the fact that there are mountain chains which stand high upon the earth's surface. They are recognized as sections of the crust which have been pushed up thousands of feet and forward many miles. Typical examples are the Appalachian ranges and the Rockies, the Pyrenees and the Alps, the Caucasus and the Himalayas. Furthermore, mountain chains that now stand high have been thrust up during recent geologic periods and there is abundant evidence that there have been older uplifts of similar character, that have been removed by erosion. Yet the sites of ancient mountains were previously flat and low and they afterwards remained flat and low for much longer periods than the time required to raise and wear down an uplift. Mountain chains are therefore to be regarded as temporary features due to some disturbance of the earth's crust, in some particular region, during a comparatively brief epoch. Evidently something out of the ordinary has happened to produce the Appalachians, the Alps, and other ranges, including the many older ones throughout geologic time. What is it that has occurred to disturb the normal stability of the crust?

The rocks of the ranges exhibit effects of intense pressure. They are closely sheared or folded. The mechanical disturbance is very great; and it often happens that large bodies of granite have been intruded into the other rocks which were the original elements of the crust before the uplifts took place. What is the power that can thus act upon a limited section? How is it developed? How is the energy stored? What are the mechanical conditions under which it works?

There have been many attempts to answer this question, but the approach is limited by the current inadequate knowledge of geology, physics, and terrestrial internal energy. A major obstacle to a satisfactory explanation has been the failure to discover an appropriate source of energy which might gradually set up a condition of stress that should be competent to disturb the normal stability of the crust and to displace a segment in the manner of a mountain movement. The facts plainly indicate some intermittent, local, occasional heating action, for which, however, there is neither cause nor opportunity in the widely accepted mathematical ideas regarding the internal heat of the globe considered as a cooling planet. In what follows these concepts are disregarded and an attempt is made to find a solution by considering the spontaneous disintegration of atoms or radioactivity as a source of heat and the action of heat, load, and atomic forces under strenuous conditions of pressure and temperature in crystalline rocks, as an auxiliary mechanism of great potency.[1]

TERRESTRIAL ERUPTIVITY

The concept that the globe is an eruptive planet is a basic assumption of the following discussion of orogeny. Attention is therefore invited to the evidence of igneous rocks as to ages and distribution of activity. It is no longer necessary to enumerate the geological relations of granites to show that intrusives of that nature have invaded the outer crust from below repeatedly from the Archean down to middle Tertiary (Daly, 1933, p. 119), since the lead ratios of radioactive minerals now give more precise data. The accompanying list and map of the world (Pl. 1) present the ages in millions of years of the rocks of 31 localities, as compiled by Holmes (1931, p. 313, 315, 351, 388) and checked and supplemented by Professor Knopf, Chairman of the Advisory Committee on the age of the Earth, up to January 1941. It will be noted that the youngest exposed granite dated by this method is but 35 million years old, the oldest is 1900 millions, and that there are various others irregularly spaced between these extremes. The number of rocks thus far dated is small, indeed, for so vast a lapse of time, but the sequence suffices to prove the fact of continued eruptivity. Additional estimates will, no doubt, be forthcoming, but the available data demonstrate the

[1] This paper was presented to the Cordilleran Section of the Society at the April meeting, 1940, under the title *Mechanics of metamorphic orogeny*. In consequence of continued studies, which have included discussions with atomic physicists as well as specialists in petrology and geophysics, the scope has broadened and the analysis has been intensified in such a degree as to require a different title. The original paper was moreover by Bailey Willis alone; but the contributions made by Robin Willis to these studies of the dynamics of the earth during the past and previous years is such that neither author is able to disentangle his particular ideas as his own.

widespread distribution of eruptive activity and show that it has recurred in the same general locality again and again, after lying dormant for millions of years. The cause of this long continued, persistent erup-

TABLE 1.—*Ages of rocks*

Age 10^6 years	Locality	Authority
35	Chihuahua, Mexico	Holmes, 1931, p. 348
38	Idaho	Holmes, 1931, p. 347
40–60	Colorado–Wyoming	Holmes, 1931, p. 346
220?*	Cornwall, England	Holmes, 1931, p. 309
230*	JOACHIMSTAHL, Bohemia	Holmes, 1931, p. 305
230	BREVIK, Kristiana Fjord, Norway	Knopf, Jan. 14, 1941
230	Topsham, Maine	Knopf, Jan. 14, 1941
250?*	Mitchell County, N. Carolina	Holmes, 1931, p. 342
300	Grafton, New Hampshire	Knopf, Jan. 14, 1941
300	Glastonbury, Connecticut	Holmes, 1931, p. 341
300–350	Kola Peninsula, Russia	Knopf, Jan. 14, 1941
330 or 460†	BEAVER LODGE LAKE, N. W. Territory	Knopf, Jan. 14, 1941
350	BEDFORD, Westchester County, New York	Knopf, Jan. 14, 1941
350	Branchville, Connecticut	Holmes, 1931, p. 341
400*	Divina do Uba, Brazil	Holmes, 1931, p. 360
460 or 530†	CEYLON	Holmes, 1931, p. 376
580	Mars Hill, N. Carolina	Knopf, Jan. 14, 1941
600	Santa Clara do Pombo, Brazil	Holmes, 1931, p. 360
600 or 800†	MOROGORO, East Africa	Holmes, 1931, p. 366
630*	KATANGA, Belgian Congo	Holmes, 1931, p. 361
760 or 820†	BESNER, Parry Sound, Ontario	Knopf, Jan. 14, 1941
900	PIEDS DES MONTS, Quebec	Knopf, Jan. 14, 1941
920	Gaya District, India	Holmes, 1931, p. 381
940	Jamestown, Colorado	Knopf, Jan. 14, 27, 1941
990	AUGST AGDER, Arendal District, Norway	Holmes, 1931, p. 276
1050	WILBERFORCE, Ontario	Knopf, Jan. 14, 1941
1050	Conger, Parry Sound, Ontario	Holmes, 1931, p. 326
1100	Devil's Head Mountain, Colorado	Knopf, Feb. 7, 1941
1100	Llano, Texas	Holmes, 1931, p. 330
1180	South Australia	Knopf, Jan. 27, 1941
1280	West Australia	Holmes, 1931, p. 384
1300	Impilati, Finland	Holmes, 1931, p. 292
1400	GREAT BEAR LAKE, N. W. Territory	Knopf, Jan. 27, 1941
1430*	Black Hills, S. Dakota	Holmes, 1931, p. 334
1780	Sinyaya Pala, Karelia, Russia	Knopf, Feb. 14, 1941
1900?	HURON CLAIM, Manitoba	Knopf, Feb. 14, 1941

Names in capital letters—determinations of the first order of accuracy, always somewhat more or less approximate.

* Age checked and corrected by Knopf, January, 1941.

† Two determinations on a single mineral; cause of difference not known.

? Determination of doubtful accuracy.

tivity is here assigned to the generation of heat by radioactive minerals, sparsely and irregularly distributed throughout the mass of the globe.

In regard to the conditions from which terrestrial eruptivity may spring we may for the purposes of this discussion contrast two hypotheses. The one proceeds from the assumption of a once completely

molten globe, an assumption which in turn follows from speculations regarding the origin of the planet (Jeffreys, 1929, p. 147; Russell, 1935, p. 80). From that line of reasoning follows an inference, namely, that erupted bodies represent residual molten material, which for some reason did not solidify, though enclosed in the mantle, which did.

Alternatively we may start from the assumption of an earth which had reached its actual structure and has long had, as it now has, a molten core within a thick solid mantle. Preceding phases may be left to astronomical speculation and geologic reasoning may be based upon existing facts. The existence of radioactive minerals is such a fact. Let it be assumed that they have always been heterogeneously distributed, in minute proportions, even in relatively rich ore bodies, and in minor proportions down to negligible traces or none at all in general. If the heat generated by them in any mass, however slowly, exceeded that lost by conduction, melting must locally ensue eventually. In time a globule of molten rock would necessarily result and when large enough it would rise to the surface and appear as an intrusive or eruptive body (Willis, 1932, p. 193-226, 214; 1938, p. 603-614, 605-607).

Several possibilities of terrestrial activity present themselves under this assumption, according to the original or primeval distribution of active substances. We may assume that they were concentrated from the start in an outer shell, but if so, eruptivity attributable to them should have run down. Or we may suggest that they were always concentrated in the mantle, but if so the irregularity of eruptivity still seems difficult to explain. Or we may postulate their distribution in all parts of the primeval globe, more abundantly, perhaps, toward the center. Then we might suppose that any molten globules developed near the surface would have been erupted quite early in geologic history, that others, more deeply seated, would have appeared later, and that the activity continuing after more than two thousand million years had a very deep origin.

We recognize that a molten core is encased in a solid mantle at the present time, and it is also a sound inference that heavy substances are concentrated in the core. If radioactive elements assembled in the same manner as other heavy constituents did, we should expect to find them there. We might then explain the inelastic, molten condition of the interior as an effect of their heat energy and, since they have not yet had time to complete the process of disintegration, we should expect continued melting at the lower surface of the mantle. As the writers see it this is the probable condition. It presents a bright prospect for our globe, if not for humanity. It also offers an inexhaustible source of eruptive material, up to the stage of complete melting of the globe.

According to these concepts globules of magma, of volumes commensurate with large batholiths or outflows of plateau basalt, have risen from the core or have developed in the mantle ever since the core and mantle acquired their present relations of centrosphere and envelope. Globules of adequate volume must rise and ascending must experience the changes of environment, changes of pressure, temperature and mineral association, which are characteristic of different levels in the mantle. (Gutenberg, 1939, p. 162; Lambert, *in* Gutenberg, 1939, p. 342; Washington, *in* Gutenberg, 1939, p. 91-105; Adams and Williamson, 1925, p. 250-257.) The general law of adaptation to environment runs through Nature and even minerals conform to it. Without venturing upon the petrological problems of the descent and evolution of rocks (Daly, 1933, p. 319-356, 566-572; Bowen, 1928, p. 303-320) we may fairly reason that heavy atoms and compact molecules [2] and crystals, whether original or differentiated, would tend to linger in the depths, under great pressures, and that light atoms, less compact molecules, and crystals, whether original or differentiated, would ascend into the outer zones, where they would be favored by lower pressures and more spacious surroundings. Furthermore, we may reason that minerals would crystallize out and remain behind or would remain in solution as the magma ascended into cooler zones, according to their order of crystallization. And it may also be inferred that more fluid magma, such as the basaltic, would be squeezed out and become separated from more viscous magma, such as the granitic.

It appears probable that these simple separations might suffice to bring about in the mantle such a distribution of heavier and lighter rocks as that calculated by Adams and Williamson (1925, p. 250), ranging from pallasite to granite. So long as the process of atomic degeneration continued to generate heat, the eruptivity would continue. To bring about an approximate distribution according to density, the process would require persistence of ascensive eruptivity during a very long time, so that the entire solid shell or mantle of the globe would be affected at one time or another. Since the activity has continued during 2000 million years and may have gone on during 3000 million (Russell, 1935, p. 21-22), it may be thought that the actual condition has been reached by that process.

CRUSTAL MOSAIC

The effect of long continued eruptivity and of the rise of molten masses toward and to the surface would be to replace any primeval

[2] The term molecule and its adjective, molecular, are here used to designate a crystal unit, a unit cell containing the constituent atoms in characteristic number and arrangement, "representative of the indefinitely extended whole" (Wyckoff, 1931, p. 48).

crust by one composed of intrusive and extrusive bodies. What any earlier condition of the outer surface may have been can only be conjectured. We may, however, follow Daly (*in* Gutenberg, 1939, p. 46) in guessing that basalt formed a world encircling layer at some period of crustal development, and we may postulate that the great batholiths of Archean time intruded that shell. It is the habit of basalt to rise through fissures because of its fluidity and it appears probable that the basaltic floors of the oceans had that origin, whatever their ages. Their surficial shapes may have been irregular, but the terrestrial bubbles from which they rose should have had rounded forms, which may now be identified in the individual minor basins that constitute the great depressions. Batholiths, as defined by Daly (1933, p. 113), demonstrate a strong tendency to conform to arcuate trends and thus suggest that they have been directed by rounded subterranean masses in their intrusive ascent. The action may be likened to the escape of liquid pressed out around a cork. To what extent this is true of large Archean individuals remains to be ascertained, but the arc is the typical form of later granitic intrusions, as it is of volcanic alignments. Throughout what follows it is assumed that the crust of the earth consists of a mosaic of rounded discs of basalt, possibly with similar discoidal, tack-shaped patches of granite, and in general with arcuate intrusions of granite. The latter are commonly intimately related to orogenic belts, as has been emphasized by Daly (1933, p. 113-120).

The fact that the crust is made up of many erupted masses of basalt and granite, which differ greatly in age, strikes at the root of theories that spring from the assumption of an ancient crust in which ocean beds and continental platforms had in some unexplained manner assumed the geographical relations they now have. Dana's idea of continental nuclei takes on more definite meaning when it becomes possible to date the Laurentian shield as about 1000 million years old and to distinguish the Appalachian core as a relatively late addition only some 260 million years old, and the Pacific Coast batholiths as of Mesozoic or Tertiary ages. Eastern Asia is built largely of Mesozoic and Tertiary eruptions (Teilhard de Chardin, 1940), and Western Europe is a modern appendix to the Russ-Siberian nuclei. It becomes necessary to recognize that each continent has been an archipelago of islands of sub-continental size, the insular elements of which have been united by intrusions and orogenesis, during pre-Cambrian, Paleozoic, and more modern ages (Willis, 1939, p. 489-491).

The concept of an archipelago contrasts with that of a continent in lack of unity. Between the relatively high standing islands were submerged troughs in which accumulated sediments of one geologic age

or another. They now constitute mountain ranges or the stumps of vanished mountains and the record demonstrates the repeated action of those forces that actuate orogenesis. The effects of that process, so far as they affect the zone of fracture and folding are to be seen in lofty mountain chains of Tertiary and Pleistocene age. Their study demonstrates great compression and lateral displacements, the roots of which lie in the depths beyond our reach. To know the conditions in the foundations it is necessary to examine the bases of more ancient heights, such as the Laurentian gneisses of Canada and other fundamental metamorphic rocks.

DEEP-SEATED FOUNDATIONS

In describing the Laurentian of Canada Sir William Logan in 1863 wrote of the "orthoclase gneiss":

> "A great portion of the rock is fine grained and, though the constituent minerals are arranged in parallel layers, no one constituent predominates in any layer to the exclusion of others; but even in their subordinate arrangement there is an observable tendency to parallelism." (p. 23)

Logan's observations are amplified by Frank Adams (1893) in a description of the Grenville series of the Laurentian system. His detailed account is too long to be quoted but of the "Fundamental gneiss" and Grenville series he says in part:

> "How much of the Fundamental gneiss consists of eruptive material is not known. The indistinct foliation, in many cases at any rate, is not a survival of original bedding, but is clearly due to movements in a plastic mass. . . . The evidence accumulated goes to show that the Fundamental gneiss consists of a complicated series of rocks of unknown origin, but comprising a considerable amount of material of intrusive character.
>
> "In certain parts of the Laurentian area, and notably in the Grenville district, the Laurentian has a decidedly different petrographical development. Orthoclase gneiss is still the predominating rock, but it presents a much greater variety in mineralogical composition and is much more frequently well foliated, often occurring in well defined bands or layers like the strata of later formations. . . . The rocks of this series, though generally highly inclined, over some large areas lie nearly horizontal or are inclined at very low angles, but even in such cases they show evidence of having been subjected to great pressure, resulting in some cases in the horizontal disruption of certain beds."

Dawson (1901), in the course of studies of the Rocky Mountain region, distinguished the Shuswap series, a "complex of crystalline rocks," which "very closely resembles those of the Grenville series"—the resemblance extending to the nature of their association with the foliated rocks, which in turn closely resemble the so-called "Fundamental gneiss" of the same region. After describing the foliation of the Shuswap and commenting upon the parallelism of the strata or foliation with the overlying Cambrian, he says:

> "It seems probable that the foliation of the Shuswap rocks may have been produced rather beneath the mere weight of superincumbent strata than by pressure

of tangential character accompanied by folding, and that both these rocks and those of the Cambrian were at a later date folded together. In the Archean of eastern Canada, foliation still nearly horizontal or gently inclined at low angles often characterizes considerable areas and appears to call for some explanation similar to that above suggested."

(*See also* Daly, 1912; 1917; Brock, 1934.)

In quoting these factual descriptions it is desirable in connection with this discussion of metamorphic action to call attention to the flat attitude of the foliation over wide areas, the parallelism of layers resembling strata, and the intimate association of igneous intrusives with foliated rocks of indeterminate origin.

James Gilluly (1934) has made an instructive contribution to the study of the type of metamorphism here thought to be characteristic of the cover of an asthenolith. Applying the methods of microscopic analysis employed to determine the orientation of minerals in the "fabric" of a rock, he examined specimens from the Shuswap terrane. From his detailed technical description we may glean certain facts.

"The rock showed pronounced linear parallelism of minerals within the plane of schistosity. Furthermore, although the schistosity in the biotite schist [one of two specimens analyzed] appears very definite and in planes rigorously parallel, that in the gneiss is composite and wavy, so that the rock, when viewed along the direction of the linear parallelism, appears to be composed of lenses; when viewed normal to the linear elements, however, the schistosity is nearly as regular as that of the biotite schist."

Gilluly then illustrates by diagrams the orientation of the biotite and quartz grains in the rocks and concludes in part:

"The symmetry of the diagrams, instead of conforming to a *normal* to the schistosity, conforms to a line *in* the schistosity . . . Shearing in the rock can hardly have been important along other planes than those of the schistosity without becoming apparent either in the textures of the rock or in the orientation diagrams." (p. 198)

"It seems to me that these diagrams furnish evidence that in these particular rocks, the *flow* cleavage occurs in the shearing planes and not in the plane of the major axis of the strain ellipsoid. It has of course long been recognized that in continued deformation the planes of shear may approach almost infinitely closely to the direction of rock elongation, although never actually coinciding with it.

"Although it seems conclusive that the metamorphism of these rocks is not static, it is not justifiable to conclude that load is thereby excluded as an important factor in bringing about the deformation recorded in the rocks. If we assume a column of rock of the necessary thickness (and with temperature gradient and solvents appropriate to produce flowage simply by superincumbent load) there must be ordinarily an extension of the layers in some horizontal direction. . . . These horizontal extensions must integrate into very large displacements if such conditions obtain over a considerable area. The differential movements between rock particles as small as grains . . . may each be slight, but their sum in a geosynclinal area may mean a horizontal displacement of huge rock masses with respect to the basement. . . . The results may be large mass movements . . . whereby load metamorphism merges into dynamo-metamorphism." (p. 199)

It will be noted that the concept thus presented by Gilluly is purely mechanical, involving simple shear and excessive load. That meta-

morphism should result on the shearing planes would be expected, under the conditions of general high temperature and of strain accompanied by rise of temperature due to friction. And, since shear planes in a highly plastic, overloaded, creeping rock would be rotated to a low dip, the attitude of the structure would approach the horizontal.

Buddington's thorough investigation of the igneous complex of the northern Adirondack region of New York State furnishes another illustration of metamorphism in the solid state (Buddington, 1939). The rocks are crystalline schists, gneisses, granulose rocks, and metamorphosed sediments of the Grenville series. They present phenomena of foliation in relation to flowage and shearing together with those of intrusions.

Buddington states (p. 306)

> "A study of the relationships and variations in the degree of dynamic crushing, recrystallization, and reaction to form new minerals in the igneous rocks of the western and northern Adirondacks, as presented in this paper, appears to necessitate the hypothesis that the foliation and microstructure as now seen was developed largely during deformation in the solid state, . . . with implicit recognition of the principle that for the most part the rocks have yielded during plastic flow of the solid along pre-existing structures dependent on primary magmatic banding or flowage planes."

From the preceding quotations it would appear that rocks of the Laurentian, Shuswap, and Adirondack terranes present types of metamorphic foliation such as should be developed in course of recrystallization under excessive load at high temperature. Pronounced movements of the nature of plastic flow or creep are demonstrated and intimate shearing is noted on microscopic as well as macroscopic scale.

It is apparent that the change of form which any mass of foliated schist has undergone comprises shortening of one dimension with elongation of one or both of the two dimensions normal to that one. In the case of flat-lying schists such as have been described above, the vertical is the one shortened and the horizontals are the ones elongated. It is of interest to consider the proportions of these changes in terms of some original diameter taken as 1 in all directions. Comparative measurements on individual crystals yield certain minima.

Leith (1905) measured hornblende crystals from unaltered igneous rocks and also from similar metamorphosed rocks and found that the relative length of the columnar axis had increased in the latter as 30/25 and even as 75/20; *i.e.*, from 1.2 to 3.75 times. Trueman (1912), measuring biotite crystals, found a relative elongation equivalent to 1.4, or somewhat more than that for hornblende. Recalling the fact that this metamorphic elongation is the final effect and that it is preceded and accompanied by plastic flow or creep on planes between crystals and on partings between layers, it becomes evident that the forced ex-

tension of a layer of rock undergoing these changes must be more than three or four times its original horizontal dimension and may easily be 10 or more times that unit.

In those metamorphic schists the presence of igneous intrusives in intimate association with the foliation, as in *lit-par-lit* relations, is characteristic. As far as one may judge from the exposures of the deep-seated metamorphics which represent one-time foundations of the crustal mosaic of continental areas, that foundation has been squeezed out laterally and has extended by recrystallization under excessive load.

MECHANICS OF CRUSTAL STABILITY AND FAILURE

GENERAL STATEMENT

Before attempting to trace the life history of an eruptive mass within the earth and to deduce the geological consequences of its development, it is well to review briefly a few of the fundamental mechanical relationships involved.

STATIC SOLID CRUST

The difficulties presented by the problem of finding a source of energy and a mechanism capable of producing orogenic deformation of the earth's crust may best be realized by consideration of the normal condition found therein in the solid state.

In the first place, there is the very great strength of the rock itself. At the surface rocks are strong relative to the load which they support. This load increases directly with the depth, and one would not have to go very deep to reach that level at which the load would be sufficient to crush the rock, were its strength only that found at the surface. It is well established, however, that confining pressure greatly increases strength, and that the depth at which the load equals the crushing strength is therefore proportionately increased (Fig. 1) (Adams, F. D., and Nicholson, J. T., 1901; Willis, B., and Willis, R., 1934, p. 426, diagram). The downward increase in temperature has the reverse effect, and tends to raise this level. Though the relative rate of increase of these three factors is not known, it is generally agreed that the downward increase in load, aided by increasing temperature, is more rapid than the rise in the strength of the rock, and that below a certain point the weight of the overlying material would crush the rock, were the lateral support removed. The depth to this point would vary widely for different materials and under different conditions of temperature, but in general it is thought to lie at about 25 to 35 miles.

Above this level it is obvious that any differential load, due either to elevation or specific gravity, would be inadequate to cause failure of

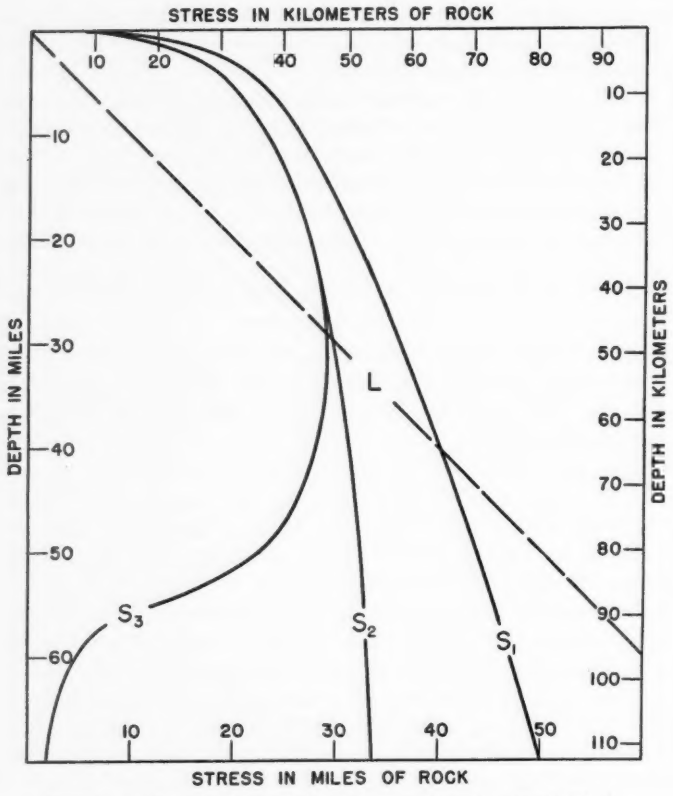


FIGURE 1.—*Hypothetical relations of strength* (S) *to load* (L) *in earth's crust*

S_1 shows strength at surface temperature. S_2 shows probable modification in solid crust by downward increase in temperature. S_3 indicates the weakening effect due to excessive temperature and near melting over an asthenolith. Below the point where each curve crosses L, the rock is potentially crushed. (Modified after B. Willis, "Geologic Structures.")

the foundation, and that due to the lateral support, the actual depth at which a variation in load alone might become effective would be much greater.

In the second place, the elasticity of the solid crystalline crust should be taken into account. Its effect is to absorb or disperse any differential stress applied over a limited area, thereby increasing the magnitude of such stress required to produce deformation. This may be illustrated

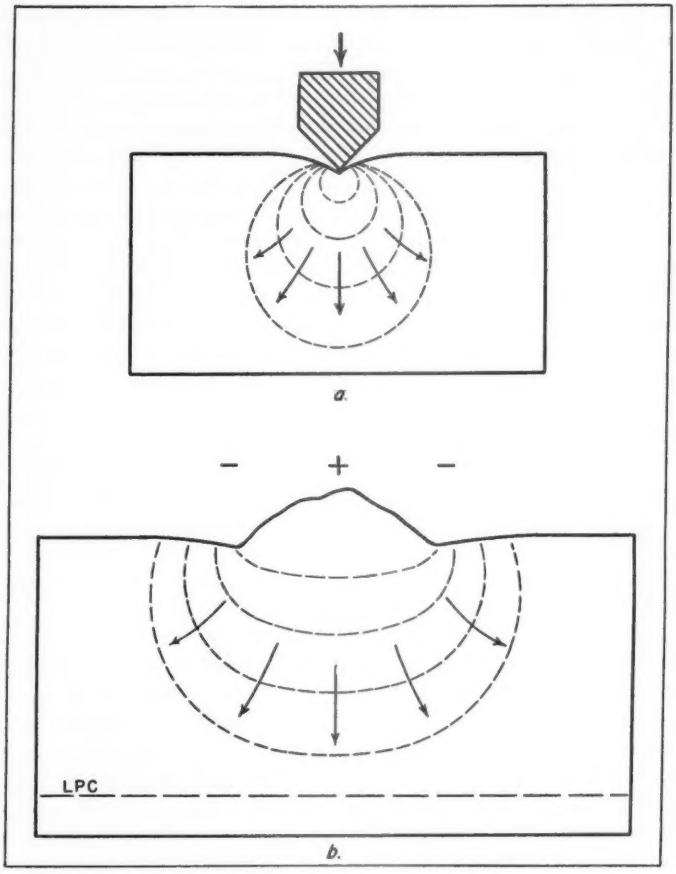


FIGURE 2.—*Elastic support of local loads*

(*a*) Dispersion of a locally applied stress in an elastic body. Dotted lines are lines of equal stress intensity.

(*b*) Support of an excess mountain mass out of equilibrium by the elasticity of the crust. Plus and minus gravity anomalies are suggested over and adjacent to the mass. Adjustment does not penetrate to the level of potential crushing (LPC).

by the load on the crust produced by an isolated mountain mass. Under static conditions this load is balanced by elastic compression, not only of the material directly under it, but also adjacent to it. The lines of stress at its boundaries radiate outward as well as downward. The load is thus distributed over a wider area, and the differential stress

dies out, both away from the mass and downward (Fig. 2). This concept introduces area as an important factor in determining the effectiveness of an unbalanced load or stress. The greater the area, the greater the distance to which such a stress may penetrate. In the case of an excess load (*i.e.*, a local load greater than average), unless it penetrates below the level of potential crushing, it cannot be effective in promoting deformation. This has an important bearing on the concept of isostasy, and determines the lower limit of the size of masses which may become isostatically adjusted. The excess mass of those of greater area, such as plateaus, would penetrate to the level of adjustment; that of smaller masses, such as mountains or even mountain ranges, would be supported elastically by the crust. The artificial concept of the earth's crust as a group of independent columns of varying specific gravity, in balance along vertical shear planes, does not, therefore, represent the conditions, and should be modified in accordance with this principle.

The foregoing considerations indicate that the effective force required to deform a segment of the crust must be very great, probably far greater than can be achieved through gravitational differences in the solid state. Factors should be sought, therefore, which may localize the stresses and promote mobility in and weakening of the crust. It is thought that these may be found in the formation of bodies of magma or asthenoliths.

CHANGES DURING MELTING

Attention may be directed briefly to the effects produced during the melting of a body of magma within or below the earth's crust.

First, as the temperature rises, there is a slight expansion of the mass, which is noteworthy because it occurs in the solid state, and therefore affects all three dimensions. There is, in consequence, a slight tendency toward uplift, together with a slight radially directed expansion, which may become important more through the weakening of the surrounding material and the development of inclined shear planes upward and out from the melting mass, rather than through the actual magnitude of the displacement.

Second, this directed expansion is followed by a larger one, during the change from the solid to the liquid state, which may be approximated as about five per cent of the volume of the melting mass. This differs from the first in that the stress exerted becomes hydrostatic, as the change from solid to liquid occurs, and should therefore find relief only in the direction of least resistance. This would normally be upward, and the principal effect would therefore be uplift which, during the development of a magma body of large proportions, might

conceivably become measurable in thousands of feet. It is definitely limited, however, by the size attained by the molten mass, and by itself would probably be inadequate to achieve the sustained thrust required for horizontal displacements measurable in tens of miles. Furthermore, it would develop very gradually, and the resultant uplift might be matched by the rate of erosion, so that no great elevation would be achieved in the area above the melt.

It is important, however, to note the difference between the nature and locus of this stress and that exerted by an excess load on the solid crust. The latter, as already noted, would be supported elastically, and would be less effective at depth. Acting on the solid mass below, it would have to crush this before it could become effective horizontally, still further increasing the amount of stress necessary to cause deformation. The hydrostatic force of the magma, on the contrary, is exerted at the level of the top of the melting mass, where it may be most effective on account of local conditions of temperature. Furthermore within the melt the horizontal component is as great as the vertical. Finally, this force is resisted not only by the weight of the cover, but also by the resistance of the solid crystalline crust to deformation. At the margins it would be dispersed elastically in the cover, increasing the potential resistance even more. As a result, a much greater differential stress could be developed than by differential loading. And yet, as the source of this expansive force is, by postulate, radioactively generated heat, it must be assumed that this force would develop to and beyond the potential resistance to uplifting offered by the cover.

The third effect of melting is the change in specific gravity of the material which passes from the solid to the liquid state. This, of course, gives the mass buoyancy, and disturbs the previous conditions of equilibrium. It is suggested that this change may be the most significant in the development of a stress equal to the demands of orogenic deformation. Heat, thus transformed into a simple gravitational differential, may through growth over a long period of time become the force adequate to the task of promoting the displacement of mountain ranges.

STRESS RELATIONSHIPS OF A MOLTEN MASS

It may now be assumed that a magma body of large dimensions, both lateral and vertical, has formed at some level well below the outer competent crust. In order to simplify understanding of the stresses developed thereby, arbitrary mechanical conditions may be assumed, it being understood that these would not be found in nature, and that actual conditions would lie in some middle ground between the extremes chosen for purposes of illustration.

Attention is directed to the stresses between the magma body and its walls. Two extremes may be considered. If no erosion were to occur during the period of expansion and raising of the cover, there would be a stress directed outward against the wall, at the top of the asthenolith, equal to the load difference due to the height of the raised cover plus the elastic resistance of the cover. Downward from the top of the molten mass this stress would diminish, due to the higher specific gravity of the wall column, until at the bottom of the magma body the two columns would be in balance.

At the other extreme would be the case in which erosion had maintained a nearly level surface during the rise of the cover due to expansion of the melt. In this case the greatest weight difference would be at the bottom of the asthenolithic mass, and it would be in favor of the wall column, which would therefore exert an inward pressure tending to squeeze the bottom of the molten body and raise the entire asthenolithic column, transmitting the stress hydrostatically to the top of the magma, where it would act upward on the cover and outward on the walls in the same manner as the expansive stress due to melting. As in that case, the potential resistance to uplift would be greater than the load, by the amount necessary to deform the cover. The essential difference between the stress due to volumetric expansion and that due to buoyancy lies in their duration. The extent of deformation due to expansion is limited by the volume of the melting material. That due to buoyancy is limited only by the distance within the crust through which the asthenolith may rise before it either finds its balance or cools and loses its buoyancy. The latter, therefore, may continue to raise the cover until the excess load due to its superior elevation, plus its own resistance to deformation, exceed the potential resistance of the adjoining segment of the crust to horizontal deformation. When this point is reached, *horizontal displacement succeeds vertical uplift, and orogenic deformation may begin* (Fig. 3). Furthermore, this need not mark the end of the asthenolithic rise, which may continue until horizontal displacements of miles or tens of miles are reached.

It is pertinent to consider the relations of the various dimensions of the asthenolith to the effectiveness of the stress developed. Height is the most important. As the stress developed is proportional to the difference in weight between the wall column and the molten mass, the greater the height of the latter, the greater the stress. The load difference must not only develop an outward force at the top of the magma, sufficient to overcome the resistances within the crystalline crust, but must also crush the base of the wall column to cause it to thrust inward

against the bottom of the magma, and then overcome the high viscosity of the magma itself, before it can be effectively transmitted to the top.

Length of the molten body bears a relation to the effectiveness of the lateral pressure, on the principle controlling the efficiency of loads;

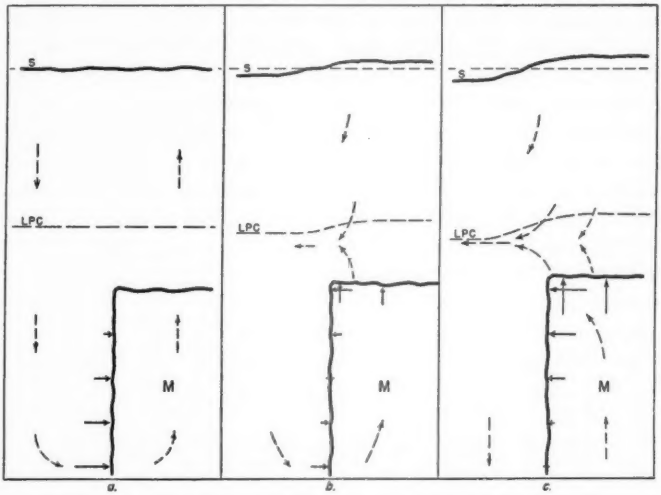


FIGURE 3.—*Development of stresses in and around a molten mass*

(a) The molten magma (M) lies below the level of potential crushing (LPC). Solid arrows indicate stress differentials developed by difference in weight of magma and wall rock. Dotted arrows show direction of possible motion. (b) If the asthenolith rises, the surface S is warped, the wall column sinks, and the cover rises. As the magma column gains height and weight the point of inflow toward it moves downward, and an outward stress develops at the top of the molten mass. (c) When the resistance to uplift (the weight of the cover plus the elastic resistance to warping) exceeds the resistance to lateral thrust (weight of the wall column plus its strength) the lateral thrust becomes effective and orogeny may be initiated.

that is, a local pressure may be absorbed elastically by the solid crust, whereas pressure on a more extended surface penetrates farther and more effectively. An intrusion a hundred kilometers long would thus produce greater deformation than one 10 kilometers long, other things being equal.

Breadth, if not too narrowly limited, does not affect the lateral thrust, the relation being the same as that of a reservoir behind a dam. Indeed a proportionally broad cover would offer less resistance to uplift and consequently develop less lateral pressure in the magma.

These considerations bear upon the proportions of mountain uplifts and the amount of horizontal displacement.

Depth of emplacement would also be a critical factor. The top of the asthenolith should be deep enough so that the cover could offer effective resistance, yet not so deep that the horizontal thrust could not find relief toward the surface on inclined shear planes. There is good reason to believe that transformation of the vertical into horizontal stress may be more effective in the base of the solid cover above the top of the magma body than around the upper margins of the latter. The liquid would tend to localize its effectiveness to points of weakness, such as potential shear planes, to work out horizontally itself, or "tack-top" the intrusion, and dissipate its energy rather than apply it uniformly to a broad area and so to displace large masses. The base of the cover, however, may be thought of as squeezed between the upthrust of the magma and the load and resistance of the cover above. Being itself a solid, it would tend to store and direct the stresses, and render them more effective. Finally it is thought that there is a mechanism inherent in the shearing of crystalline rock which may make its failure and elongation more effective in deforming the adjacent mass than the uniform, steadily applied hydrostatic pressure of the magma could be. This mechanism is discussed later in connection with the shearing of crystal lattices.

The mechanical concepts presented above have been considered briefly, stripped of their relations to many pertinent factors, such as the crustal environment, the nature and composition of the magma, differentiation into heavier and lighter fractions which would exert varying gravitative stresses, and so on, in order that a clear picture of the inferred origin of the deformative stress may be obtained. The development of a molten body or asthenolith is next to be discussed.

DEVELOPMENT OF AN ASTHENOLITH

MELTING STAGE

Let it be assumed that there is a potential hot spot, comprising a mass of rock situated in the upper part of the asthenosphere (Barrell, 1914, 680-681). Whatever its earlier history may have been it is supposed to have reached the normal state of an elastic solid in the mantle, with the temperature just below melting. By hypothesis it contains heat-generating elements, which gradually raise the temperature till melting begins. Thereafter increments of energy are taken up as latent heat.

In order that heat shall accumulate, its generation must proceed at a rate in excess of that of escape by diffusion, conduction, and heat-absorbing reactions. An equilibrium between the two rates would mark the upper limit of the hot spot at any time. The limit cannot be defined

as occurring at any certain depth, even if we accept the estimates of the normal thermal gradient, for the generation of heat depends upon the proportion of active elements in any given case and the rate of escape varies inversely as the depth below the surface, other things being equal. Another unknown factor is the influence of radioactive elements in the crust above the hot spot, since they may supply a part or all of the escaping energy or even contribute to the heat below.

According to estimates of the thermal gradient within the earth at moderate depths (Gutenberg, 1939, p. 162) a melting temperature for peridotite, about 1400° C., should exist at a depth of about 100 kilometers; but since the normal gradient would be modified by heating of the hot spot a lesser depth may be assumed as an upper limit. We may note that beneath a component disc of the crust, having a similar constitution throughout, the limit would be set by fairly uniform conditions and would be practically level. It might be compared to the level bottom of a cumulus cloud, below which the moisture is in solution and above which it is condensed and is crystalline if frozen.

We may recall the fact that the major portion of the crust, down to a depth of 50 kilometers (30 miles) or more, is a rock like plateau basalt (Gutenberg, 1939, p. 103; Daly, 1933, p. 175-179). It is also a fact that in compressed mountain chains the conspicuous intrusive is usually of granitic composition. We may therefore assume that the cover of our hypothetical asthenolith is often basalt, while magma developed locally in the hot spot may be granitic. If that be the case, certain results follow, as detailed below; if in any case the conditions are different, the results would also differ; but here we assume the basaltic cover and a limited body of granitic magma under it. Granite melts at about 300° lower temperature than basalt (Daly, 1933, p. 291). Granitic magma may consequently heat up to a completely molten condition in a crucible of basalt. During that action, however, the walls and particularly the cover will be affected by the heat. We may first concentrate attention on the initial effects.

There will first be the expansive effect of heating, in the cover, for instance. The total expansion will be proportional to the diameter and will develop internal compression and centrifugal stresses. If the framework be firm the cover will be compressed and will become less easy to penetrate by gases or liquids. Since any expansion must be greatest in the lower layers of the cover, the bottom of the disc would become convex, warping either upward or downward. The effect at the surface would be to produce a rise or a subsidence, a dome or a basin.

In addition to expansion and warping we may include incipient metamorphism as one of the initial changes started in the cover as the equi-

librium of the normal state is disturbed, but the effects would not differ in kind from those which we may attribute to more pronounced alterations of the same character during more advanced stages. Here we need merely to call attention to the fact that the process develops gradually. The melting stage passes slowly into the molten and stresses develop accordingly (Fig. 3).

MOLTEN STAGE

We assume that a body of granitic rock or of rock capable of yielding granitic magma is being heated, very slowly, from the normal temperature at which it has been crystalline, to that at which it is a viscous liquid. It will presumably be a mixture of silicates whose melting intervals differ and a partially melted condition will precede the completely molten state. Moreover, as the heat generators are mineral particles, very sparsely and irregularly distributed, the melting will proceed around separated foci, each of which becomes a nucleus of a viscous, liquid globule. These will grow, coalesce, and shift about, with a tendency to ascend. Wherever the magma becomes sufficiently fluid gravitative precipitation may occur and the most liquid melt may accumulate in a superficial layer. It will also be the hottest.

The phenomena of intrusion and related conditions are next in order.

INTRUSION AND FLOWAGE

It may be suggested that in consequence of simple expansion during the initial heating, the cover would become relatively impervious and less easy to penetrate by gases or liquids. If so the early stage would be unfavorable to intrusion. But shearing on gently inclined planes rising from the upper surface of the asthenolith would facilitate intrusion. Since shearing promotes melting and the conditions of the position would be favorable, we might expect that any such plane would become a locus for molten material confluent with the magma. The growth of branches thus sprouting from the body would constitute intrusions. This seems to be one favorable condition. Nor may we overlook the penetrating action of thermal solutions. On this point we may again quote from Buddington (1939, p. 166):

> "The study of the country rock in the Grenville belt shows that thermal solutions (hydrothermal and pneumatolitic solutions as distinguished from magma solutions) have emanated in quantity from granitic magmas and have accomplished profound results in the way of addition and recrystallization, successive complex reconstitutions, and alterations of the mineral associations of the Grenville series. Indeed it is rare to find a rock in the Grenville belt, older than the granites, that has not been worked over and modified to a greater or less extent by such thermal solutions, and this includes gabbro and diorite intrusions, as well as all members of the Grenville series."

The time element enters in. The several potencies do not come into play simultaneously. The initial effect in the cover is slow creeping, due

to moderate rise of temperature over the embryonic asthenolith. It directs the beginnings of metamorphic change and mineral growth in the horizontal planes. The resulting compression induces mechanical strain and shearing, producing flattened blocks, with molten films developing locally on the shearing planes and movement of the films from loci of greater to places of less pressure as the blocks rotate. And the creeping, forcibly growing, shearing layer which forms the base of the cover is finally invaded by the more liquid portions of the underlying magma in the forms of dikes, apophyses, and *lit-par-lit* injections.

The actions discussed are thought to occur at a depth such that the superincumbent load is greater than the strength of the rock at the high temperature prevailing under the assumed conditions. This may be as deep down as 50 kilometers (30 miles) or at much less depth when the rock is heated. At whatever depth the reactions occur they disturb the conditions of support of the crust. Normal support on stable foundations is weakened and the distribution of vertical and horizontal stresses is materially changed.

ILLUSTRATIONS

The following hypothetical cases are stated and the application to actual mountain ranges is suggested to illustrate the mechanical principles described in the preceding section.

Case 1: A high plateau, presumably lifted by the buoyancy of an asthenolith of notable height and depth; proportionately great mountain range and horizontal displacement. *Example:* Tibet and the Himalayas. Evidence for the existence of the invisible asthenolith is found in the lightness of the mountain mass and the great intrusion of granite of Tertiary age.

Case 2: Plateau of moderate elevation, but great extent, very slight lateral thrust, no long mountain ranges; presumably lifted by the volumetric expansion of a broad, thin sheet of magma at moderate depth. *Example:* East African plateau (Willis, 1936).

Case 3: Domed peneplain of large diameter and moderate elevation in region long inactive. *Example:* Post-Cretaceous doming of Appalachian province, presumably attributable to deep-seated invasion of foundations by magma or to gradual development of magma by radioactive heating, with related effects.

Case 4: A depression bounded on one or more flanks by strongly compressed zones, which have been intruded by large volumes of granite and other magmas. It is assumed that the outflow of magma and the loss of buoyant support have caused subsidence, while pressure on deep-

seated roots of the asthenolith has continued to exert the lateral thrust effectively. *Example:* Japanese arc. (*See* discussion in the section on Japan.)

Case 5: A complex mountain range, intensely squeezed, exhibiting older structures displaced by younger thrusts, and repeatedly intruded by granites and other igneous rocks; and furthermore situated between relatively low zones or plains. *Example:* The Alps. Considering only the Tertiary orogenies of Oligocene, Miocene, and Plio-Pleistocene times, the Alps exhibit effects of pressure from northwest cut by thrusts from southeast (Willis, 1907). It is inferred that the Alpine orogenic zone lies between two active areas, whose periods of effective activity have not been contemporaneous. The subsidence of the Po basin is presumably attributable to failure of buoyancy and overflow of magma from a subjacent asthenolith, which was the cause of the Plio-Pleistocene orogeny.

Case 6: A large province, characterized by isolated mountain ridges and extensive eruptions of lava, including plateau basalts, and bounded in part by lofty uplifts, in part by flat-lying thrust faults. *Example:* The Great Basin, western United States. The complexity of surface phenomena plainly indicates similar complexity of subterranean conditions. The fissure eruptions of basalt may be interpreted as a typical example of the extrusion of fluid lava from a broad, shallow magma basin. The complex shearing, which has produced overthrusts, strike-slip faults, and normal faults, indicates failure of the cover over a hot spot of very large diameter, in consequence of expansive stresses, attributable to deep-seated lateral creep and recrystallization by atomic adjustment. The flat-lying overthrusts toward the northeast in the Rocky Mountain front and the similar structures along the southern rim seem to represent sections of the periphery where the framework was not sufficiently firm to resist the expanding cover. And the Wasatch and similar mountains with granite intrusions suggest the existence of granitic asthenoliths with deep roots, in the margins of the large, complex hot spot.

METAMORPHIC ACTION

It is assumed without argument that the heat and chemical reactions of the molten rock of an asthenolith will cause metamorphism of the cover, the temperature being too low to occasion melting of the latter, yet high enough to disturb the molecular bonds of the minerals. It is part of the postulate that this contact is maintained during millions of years and that consequently the heat and to some extent the gases penetrate the cover by absorption and atomic diffusion to a notable

distance. For convenience of discussion a layer 10 kilometers or more thick, measured from the asthenolith upward, may be suggested. Obviously, the rate of penetration would be a function of the intensity and the depth would increase with lapse of time.

The duration of the period of melting and lifting is of the order of tens of millions of years. For instance, the high plateau of East Africa was peneplained during Miocene time and that peneplain is now raised to an altitude of 3000 meters, more or less, presumably by the development of an asthenolith beneath it (Willis, 1936, p. 81). The elapsed time since the graded plain sloped gently to the sea is 20 million years or more.

During the long period of melting and uplift the conditions of support of the crust above the asthenolith gradually change from stability toward instability. In the normal state of the solid crust and mantle the weight of the crust is held in stable equilibrium by the strength of the rock and the lateral support of the spherical shell. At depths of 50 kilometers or more the strength of the rock is exceeded by the load and the lateral support becomes a resistance essential to maintain stability. If we call the weight W, and the strength S, and the lateral resistance to spreading H, we may write $W = S + H$, as the equation of equilibrium.

The equation holds for stable equilibrium, but it fails if for any reason either factor be changed without proportionate changes in the others. In the case under consideration the strength S weakens as the rock over the melting mass becomes heated. The overloaded layer will then tend to spread till it builds up a proportionate H, or it will displace the opposed section of the spherical shell by shearing it. Since the rise of temperature is very gradual, the weakening will proceed very slowly and the effect will be a gradual spreading by creep (Griggs, 1939). It will proceed at first within the elastic limit and, when that is exceeded, by fracture, "plastic flow," and shear.

During the prolonged initial movements, for thousands of years, plastic flow will dominate and distribute the stresses. Under the assumed conditions of high confining pressure and crushing load the adjustments to equilibrium of stress and resistance must pervade the entire crystalline mass intimately. But since the resistances are constantly being weakened by heating there can be no permanent set. Spreading by slow creep will continue.

The rock being a solid deformation proceeds by shearing and since the movement is that of plastic flow the shearing planes will be closely spaced and will be rotated from the attitude of 45° degrees, which they

would assume in a brittle substance, toward flatter inclinations (Becker, 1896, p. 434). In the course of prolonged movement, resulting in material flattening, thinning, and spreading, the rock will become a thinly foliated schist.

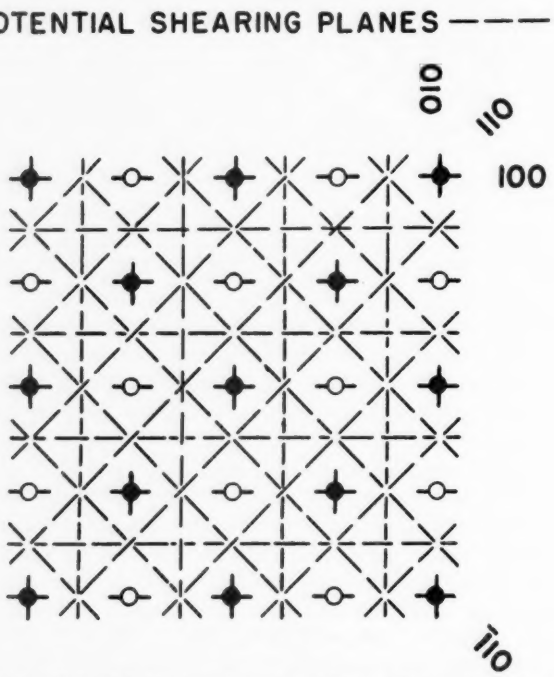


FIGURE 4.—*Potential shearing planes in cubic crystal; two dimensions*

Thus far the only stresses considered have been those due to the load resting upon and deforming a weakening foundation. But under the assumed conditions it is not merely the cohesion of the rock mass which will be overstressed, but also the bonds within the crystals themselves. That this is so follows from the fact that rocks which have been subjected to the conditions described are metamorphosed and recrystallized. One explanation of their condition implies the action of a solvent, which attacks the mineral where the pressure is greatest and flows with the dissolved solute to a position where the pressure is less. The transfer takes place under hydrostatic conditions and involves only the differential

pressures. It would appear, however, that crystals undergo deformation in the solid state (Buddington, 1939, p. 305-306). The action in that case is simply the intensification of the shearing to the degree that it affects the crystal lattices.

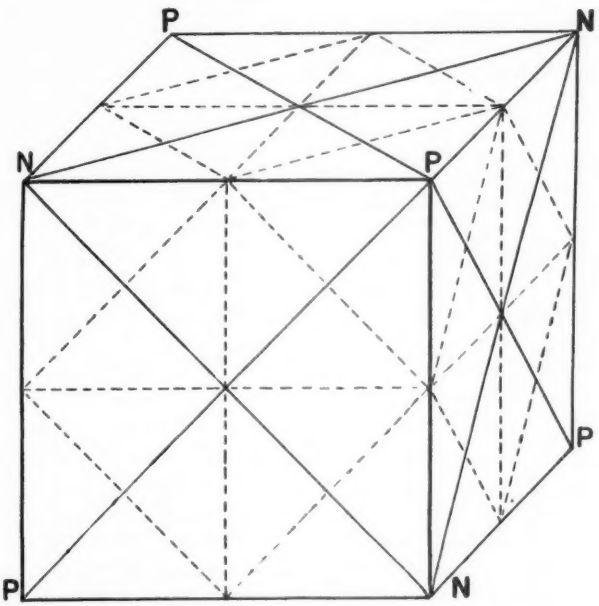


FIGURE 5.—*Potential shearing planes in cubic crystal; three dimensions*

To examine the effects of shearing within a crystal the experimental studies of Joffé (1928) and Bridgman (1936), are available.

Joffé experimented with the simple, cubical crystal, halite, in which the relation of the positive and negative charges is that shown in Figure 4, looking down on the top of the cube. Potential shearing planes strike between the ions in any one of four directions. By referring to Figure 5 it may be seen that there are two possible planes of shear for each strike, cutting off the corners of the cube at 45°, and that consequently, if the crystal be rotated through an angle of 45° the opportunities for shearing are repeated in the same number and relations. It follows that a plane of potential shear can never depart from the mathematical orientation by more than 22½°.

The ions on opposite sides of a potential shearing plane attract one another when of opposite sign and repel one another when of like sign. Figure 6A presents them in the normal relation of equilibrium. Let

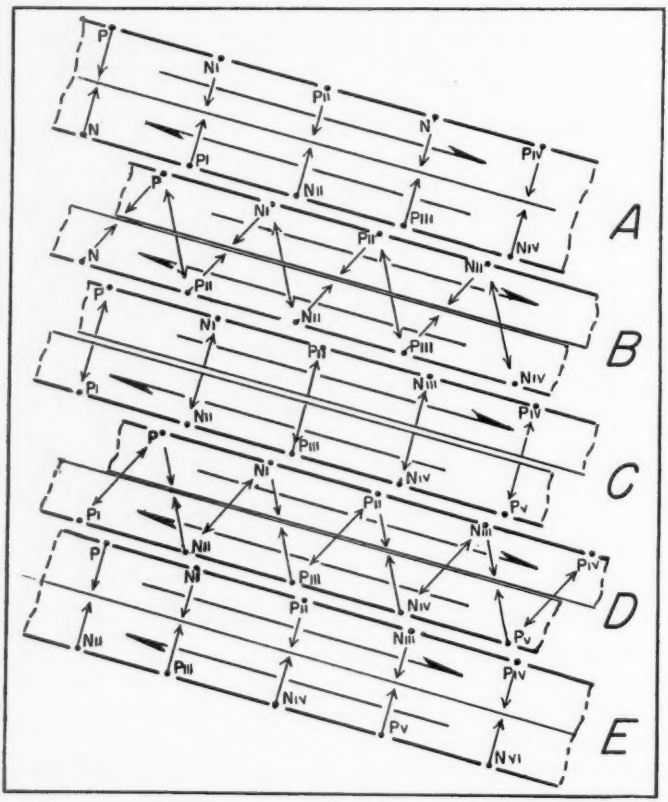


FIGURE 6.—*Effect of shear on balance of atomic attractions and repulsions in crystal lattice in 100 or 010 plane*

it be assumed that shearing occurs on the crystal plane as shown by the split arrows and that the displacement amounts to ½ the atomic distance. The relations of the ions will then be as in B. In order that this displacement may occur, the attractions and repulsions by which it is resisted must be overcome, but by hypothesis the load is superior to the strength of the crystal and the latter will yield. Let the shear-

ing progress so that there is another displacement of ½ atomic distance in amount. The result is shown in C. Ions of like sign are brought into opposition and the initial condition of attraction is replaced by repulsion. Friction on the plane will be reduced and shearing facilitated. Let the shearing proceed. It is now assisted by the repulsion and attraction, both, and the ions jump into their new positions with accelerated motion. The result is shown in E, which presents the identical atomic relations as in A. The crystal structure has not been changed but the crystal has been elongated. Joffé thus describes the experiment (p. 50):

> "We noticed that the shear of heated rock salt and zinc progresses by small jumps, each accompanied by a noise like a tick of a clock. In a quiet room these ticks are rather loud and follow at regular time intervals. Many hundred ticks may be noticed, their frequency depending on the load applied."

It was found that the frequency was a function of the pressure, whereas the magnitude of the jumps was a function of temperature. These phenomena occur when the shear is parallel to the 100 crystal plane or to the 010 plane. A somewhat different reaction is observed when the shear parallels a diagonal, 110. In that case the ions are all positive on one side and all negative on the other of the crystal plane and the attraction between them is never interrupted by displacement on the shearing plane. It is, however, alternately weakened and strengthened and the ions are drawn into their new positions by the ionic attractions during half of the action, as before (Fig. 7).

Bridgman (1936, p. 662) describes similar shearing effects in substances subjected to torque under high pressure and graphically states: "The material merely lets go to get a fresh hold, and the phenomenon repeats itself indefinitely."

Joffé's experiments were made on simple cubical crystals, in which the crystal planes are flat and extend to the external faces. Their number and consequently the number of directions of possible shear is, however, so limited that the angle between a potential shearing plane and a shearing stress may be as great as 22½°, as already stated. Crystals of the rock-forming silicates are much more complex in atomic structure and therefore offer a larger number of potential shearing planes, with the probability that the angle of divergence from a stress would be frequently less than 22½°; the chance of coincidence with moderate rotation of crystal or stress or both would therefore be increased. But the extent of any crystal plane in any one direction would be comparatively limited and the enforced displacement would be represented in any general direction by a sinuous line. The resistances would also be variable, but none could withstand the stress, under the assumption of crushing load.

We may conclude that: *Any solid crystal subject to a crushing load and an adequate differential stress must be sheared in such manner that the atomic balance will be disturbed. On being forcibly displaced to that extent that they are released from the original bonds, the atoms will be*

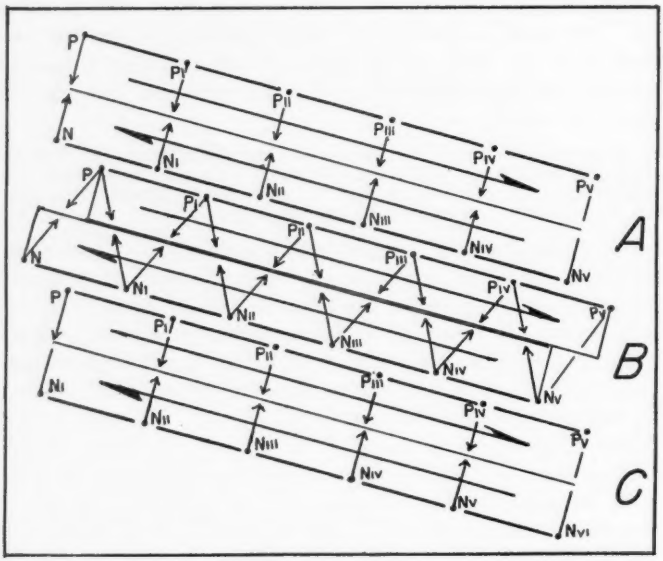


FIGURE 7.—*Effect of shear on balance of atomic attractions in crystal lattice on 110 plane*

pushed and drawn into new relations by the atomic repulsions and attractions, with an accelerated motion.

As has been noted, the differential stress upon which the action depends may be set up either by increase of load or rise of temperature, or both, and the frequency of the jumps is related to the pressure, whereas the magnitude is a function of temperature.

Inter-atomic shearing is evidently an extreme phase of deformation which occurs only when more moderate changes have been satisfied, that is, when the condition of plastic flow by macroscopic shearing no longer absorbs the total shearing force due to excess load and there is a residual stress available to shear crystal lattices. And also when the heat of the subjacent melt has so weakened the atomic bonds that they must yield. This implies that the temperature had approached the melting stage.

As the heat from the melt penetrates to higher and higher horizons the action rises with it. Shearing will become more and more intimate, more closely spaced in the lower part, and will affect more distant levels as the process of warming up continues. If and when it reaches the intensity of inter-atomic shear it sets free in the layer that is thus sheared the atomic forces, so that they act as described above; they move in the direction of flow by jumping into new relations. The jump is infinitesimally small, but it is immediately and persistently repeated as long as the differential pressure is maintained. The movement may be described as that of an *atomic current*.

It is improbable, however, that displacement would long follow a definite plane or direction. Shear always curves toward a less resistance and varying resistance should be expected in crystalline rock under the postulated conditions. Furthermore, atomic shear would develop simultaneously in many parallel or nearly parallel orientations. The rock should thus take on a wavy foliation, with innumerable thin foliae overlapping and terminating against one another. The layer thus undergoing reorganization would elongate in the general direction of plastic flow and the force with which it would act against any opposing mass would be the pressures due to the load stress and crystal elongation by atomic impulses in the same direction.

Let it be repeated that the elongation must be a maximum in the lower part of the cover and must die out upward. Then the front of the advancing layer may be compared to the edge of a chisel, with the bevel turned upward. The most intense pressure will be exerted at the bottom edge and it will tend to penetrate the opposing mass and shear off the section immediately above it. The pressure must react upon the chisel and since the reaction may equal the shearing strength it may produce local shearing in the spreading layer, which is supported on its lower face by the upward, hydrostatic pressure of the magma. Any shearing plane dipping into the viscous magma would become liable to intrusion, with the result that the magma would enter the foliated layer in intimate relations, such as *lit-par-lit*.

The reactions would continue for many hundreds of thousands of years, during which the effects of high temperature over the growing asthenolith would penetrate to higher and higher levels. The ultimate thickness of the metamorphic layer would depend on many factors. It may best be guessed by considering the estimated thickness of Archean and ancient pre-Cambrian terranes, where the characteristic structures are typically developed.

In order to expand the concept of creep and atomic flow to terms of terrestrial magnitude one may consider the size of batholiths. Even so

small a one as that of the Sierra Nevada of California has a superficial expanse of roughly 100,000 sq. kms., and if it were a circular disc would be nearly 80 kms. (50 miles) in diameter. Masses several times that diameter are of common occurrence as elements of crustal structure. But diameter is not the critical dimension since thinning and spreading by shearing and plastic flow may continue indefinitely, so long as heat and excess load operate. As previously stated, height and length are more important than breadth. A long, relatively thin crystalline body, yielding to excess load, beyond its crushing strength, may be forced to spread to many times its horizontal thickness.

Let it be assumed that an asthenolith of these general dimensions develops beneath the outer crust, say beneath a basaltic element of the mosaic. The latter may be assumed to be fairly uniform in constitution and thickness over the heating body. Gradually warming up on the bottom, expanding, creeping outward as its own weight overcomes its lessening strength, the cover will press radially outward in all directions and will be resisted without fracture up to the elastic limit of the framework. When the elastic limit is surpassed the rock of the frame will yield by shearing and will be pushed outward and upward. It is conceivable that a perfectly circular disc of uniform basalt of uniform thickness, uniformly heated, should expand uniformly, should creep uniformly, should exert uniform pressure in all directions, should meet with uniform resistance all around—and should thus cause the framework to shear everywhere simultaneously and the rim to rise equally as a circular ring. It is mathematically conceivable, but it does not make sense, nor is there any terrestrial example of form and dynamic symmetry so perfect. Even submarine basins are oval, asymmetric in every respect, including the heights of arcuate rims and the distribution of volcanic activity along them, where that evidence of subterranean heat occurs.

The structural elements of continents are even more irregular; the subterranean bodies of intrusive and metamorphic rocks constitute complexes of highly varied character. Expansion and creep in the base of the continental crust must be of unequal intensity in various directions from a central source and they must meet with very diverse resistances on different sides. Among them there must always be a least resistance toward which the resultant creep and plastic flow of the cover would tend from an early stage and toward which the resultant push must eventually direct displacement.

From the measurements on common minerals of typical igneous and metamorphosed rocks it appears that the change of form due to metamorphism amounted to an elongation of those minerals to approximately

three or more times their original lengths. It was shown by Wright (1906) that the elongation occurs in the direction of flowage and least resistance, and it follows that a rock composed entirely of hornblende and micas would grow by molecular force to that degree and in that direction. Where other minerals, such as quartz and feldspar, occur they would affect the elongation and reduce it, since they appear not to extend to the same degree. But it seems reasonable to postulate that in general the elongation due to crystal elongation alone would amount to two or more times the initial dimension of a mass of crystals.

The above conclusion takes account only of the elongation attributable to atomic flow. It does not cover the rolling out of the rock in plastic spread under the load; yet that movement must also occur in the same direction and in cooperation with the molecular change of form, thinning and lengthening the metamorphosed layer in the base of the cover.

EFFECTIVE RADIUS

Let the original length of the line of crystals, whose metamorphism produces the elongation, be designated the *effective radius*. Initially it is not a line, only a possibility; but as the base of the cover over the growing asthenolith becomes heated and the crystals adjust themselves to the new stresses, it becomes an alignment and a radiating line of stress, one line of a flat film of closely packed stresses of approximately equal intensity. The metamorphic layer will be composed of an infinite number of such films and the intensity of the stresses will be greatest at the contact with the melt, lessening upward.

The effective radius has two ends: the one would be the origin, the center, if the structure were circular, but an orogenic form is an arc only and the inner terminal of an effective radius is simply any point within the disc where opposing pressures are in equilibrium. If that point were to happen by chance to be so situated that the resistance to expansion be equal in two opposite directions, the effects of expansive pressure would appear in both directions. But such symmetry can rarely, if ever, occur. The heating that produces the metamorphic effect commonly occurs off center of any older disc and the greater mass on one side more firmly resists the newly growing stresses than the lesser mass on the other side. Expansion against the greater resistance will be checked and must react in the direction of less resistance, pushing outward away from the point at which equilibrium is established. That is the inner end of the effective radius. There is the "buttress."

The other or outer end of the effective radius is determined by the limit of the heated area, on the side of less resistance. There the displace-

ment begins and thence it grows as the molecular forces elongate the radius and thrust the opposing segment of the crust outward and upward on an up-curving shearing plane.

The front of that upthrust mass, plus the granites intruded behind it, constitute a mountain arc.

In vertical section the structure as a whole exhibits the well known architecture of a mountain range, built up of intruded, metamorphosed, and stratified rocks, sheared into rhomboidal blocks or folded, crushed together and overthrust. In plan it has the crescentic form and presents the convex front and concave rear, long since identified by Suess as characteristic of compressed mountain arcs. By hypothesis the structure extends downward and rearward to its roots in the metamorphosed layer above the site of the genetic hot spot. The crescentic form originates in the hot spot itself, in consequence of the ascent of the magma along the outside of the older mass that forms the crustal disc. The hot-spot magma is thus a local, marginal body and the mountain range which its activity produces is correspondingly limited to a partial section of the margin of the disc.

DEVELOPMENT OF AN OROGENY

The various static and dynamic conditions described in the preceding pages being postulated the initiation, gestation, and completion of an orogeny may be traced. It is necessary, however, to define an orogeny as a dynamic development which produces a mountain chain as the result of many millions of years of life. Precise definition in terms of years is not possible, nor is it probable that orogenies among themselves have been of like duration, even approximately. But the concept here presented may be illustrated by citation of examples. An orogeny, in the height of which man has evolved, is recognized in Pacific lands. It has developed during Pliocene and Pleistocene time since a similar action slowed down during the Miocene in the same areas. That is a lapse of 20 to 30 million years or more and there is no evidence of decadence. The distinction between this current orogeny and that of the Miocene is not sharp. There is no well-developed peneplain. The two might be regarded as episodes of one dynamic period and when compared with Mesozoic and earlier events of the same character, they do appear to be phases of a single great, complex action, involving the gathering, storage, and dissipation of terrestrial energy. Earth history is divided into sections by diastrophic incidents, each of which represents the expenditure of a vast amount of energy. The period of preparation, during which that energy accumulated, was one of comparative stability and was of much longer duration. It is character-

ized by the peneplain even as the "revolution" is marked by the mountain uplift. In what follows, the peneplain stage is regarded as an essential preface to the more active episode.

The initial condition from which an orogeny is believed to develop is, therefore, one of crustal stability and superficial peneplanation. Beneath an area thus characterized, ores of radioactive minerals are assumed to be introduced in the upper part of the asthenosphere. As to how? The intimate structure of deep-seated schists, which have been invaded by viscous melts or pneumatolitic or gaseous emanations is probably the best guide for inference. An alternative is the uptrusion of a molten body, an asthenolith, which is supposed to check and cool beneath the outer crust. Whatever the manner of their emplacement, radioactive ores generate heat, and if the rate of accumulation exceeds losses the temperature must rise.

Volumetric expansion of the mass thus heated will produce internal stresses and outward pressures in all directions. The condition of stable equilibrium is that the crushing load shall be supported by the rock-strength and the resistance of adjacent rock. The load remains constant, the strength is reduced by heat, and the resistance must rise accordingly, if equilibrium be maintained. That is possible within the elastic limit, but when it is surpassed shearing must ensue. Since the dominant stress is vertical and the state of the material is that of plasticity, any shearing will tend toward a gently inclined attitude and displacements will be outward in a plane approaching the horizontal.

With continued generation of heat, selective melting must ensue; magma will accumulate beneath a cover, and a flattened bubble will form. The manner in which these conditions may affect the surface by change of volume, buoyancy, and modification of stresses around the molten body has been discussed in a preceding section. Attention is here focused on the development of lateral thrust.

Lateral creep in consequence of low-angle shearing is assumed to have pervaded the solid crystalline rock above the magma. The shearing progresses between crystals and on structural planes of a crystal lattice, or on many such planes in a congeries of crystals. The crystal lattices are sheared, and a current aided by elongation of innumerable crystals is set up in the direction of the lateral thrust. The gravitative energy of the load which causes the shear and forces any atom out of its position of equilibrium is stored in the system as potential energy and is delivered with accelerated motion as the atoms jump into new positions of equilibrium. The atomic action is not confined to a layer of atoms. It extends to all atoms of the crystalline mass involved in the flow. The direction of displacement is fixed by the plastic creep toward the least resistance.

There is no reverse movement. The mass has a glacierlike motion, imposed upon it by gravity and rendered more potent to displace an opposing mass by the internal energy of the crystal as the atoms are forced to let go and leap into new positions. The effect is to elongate the crystals of the entire layer and consequently to expand the layer itself, and the movement must continue while the load pressure continues effective as a shearing stress. The limitations of that pressure therefore set bounds to the thrust.

It is postulated that the balance of the support of the outer crust is disturbed by the buoyancy of a magma body, which rises initially in consequence of the expansion due to melting and subsequently because the melt is relatively light as compared to the solid walls around it. The excess of load pressure thus produced is the cause of the plastic flow, of the shearing, and of the atomic current; and those activities must cease when it becomes exhausted, that is, when the excess of load over the magma is removed by erosion or subsidence. The mechanism reaches stability again, without having thrust any mass above the original level of the surface. To get a mountain uplift some additional force is required. It is found in the mechanical, hydrostatic lifting pressure of the magma.

As was stated previously, the column of magma and superincumbent crust is lighter than an adjacent column of solid rock of the same height, measured from the bottom of the magma to the surface. When both are failing columns the heavier pushes in upon the lighter with a stress which is greatest at the bottom and that maximum pressure is transmitted hydrostatically to the walls around the magma body, including the top. At that level it tends to force the magma most forcibly into any existing or potential parting. At that level the creeping, expanding section of the cover exerts the maximum thrust and most effectively develops a major shear between its base and the top of the wall around the magma. Initial shearing is thought to have been started by the expansion due simply to heating; more complex and intimate shearing and displacement are regarded as having resulted from the movement due to load, tangential thrust and atomic impulses; ultimately the magma intrudes on the shear planes, acts as a lubricant to reduce friction, and lifting the sheared segment carries it forward by virtue of the hydrostatic pressure derived from the deep level of the bottom of the molten body.

At the base of the sheared segment lies the major shear which separates it from the undisturbed portion of the underlying mantle. It may be called the "sole," or sole-fault. Magma, intruding along the sole will co-operate with the tangential thrust to develop it. It will extend and curve upward till reaching the surface it becomes the mountain front.

This simple picture is subject to modification by the accidents of older crustal structures and by local stresses. To what extent that is true may be inferred from the complexity of structures characteristic of mountain ranges. But the preceding study is offered as an attempt to suggest a system of forces, comprising heat, gravity, and atomic bonds, which is adequate to produce mountain chains in the general manner described.

The decadence of an orogeny follows upon the exhaustion of the motive power, heat. The radioactive elements which produce that energy are involved with other constituents in the magma they produce. They are carried out with it, and exhaustion ultimately follows. Let us recall the fact that the magma is forced out by encroachment of the walls at the bottom. The crucible becomes shallower, the extensive pressure grows correspondingly weaker, and it eventually becomes incompetent any longer to overcome the resistances. A static condition succeeds the dynamic life of the asthenolith, and erosion finally levels off the upthrust mass.

JAPAN

JAPANESE AREA IN GENERAL

The Japanese Archipelago presents the form of a curving mountain chain, whose summits stand some 4000 meters (15,000 feet) above the flat bottom of the Sea of Japan. Viewed from the Pacific bottom it is even higher, rising 6000 meters (20,000 feet) above that level. It is a great mountain range, submerged to within 1000 meters (3000 feet), more or less, of its crests, not considering the great volcanoes. The islands consist of a variety of rocks, among which metamorphosed Paleozoic sediments constitute nuclei and by their marine character indicate that in Paleozoic time the sea extended uninterruptedly over their place of deposition. That is to say, the Japan Sea was then confluent with the Pacific. There is no definite evidence of previous lands within the area. The mountain chain belongs to the framework of the Pacific, to the great, young mountains of the West in the Americas and of the East in the Orient, in age as well as in position.

Our Japanese colleagues have during two generations executed surveys, which have produced the detailed geologic map of their country and voluminous accounts of the stratigraphy, paleontology, petrography, and structure. We unfortunately are unable to profit by that large part which is printed in Japanese characters. In the description which follows, the available abstracts, published in other languages, have been utilized, but the senior author of this paper owes more to the courtesy of Professors Bunjiro Koto, Hisakatsu Yabe, Teiichi Kobayashi, Geichiro

Kobayashi, and other geologists with whom he has been privileged to confer in extended visits during 1926 and 1937.

The great curve of the islands comprises several minor arcs and nodes, as shown on the accompanying map (Pl. 2). They differ somewhat in rocks and structure, but in general consist of metamorphics, granites, Mesozoic and Tertiary sediments, and volcanics. The structure exhibits effects of shearing, rotational movements, thrusting, and folding, often of great complexity, and clearly demonstrates intense compression.

Our present purpose is not to describe the geology of the Archipelago (Willis, 1940), but to utilize certain facts and relations in testing the validity of the concept of the relation between eruptivity and mountain building. We direct our attention specifically to the southwestern part of the Japan Sea and the Tsushima Arc, where there are significant evidences of a hot spot and of radial out-thrusts toward the southeast and west.

To trace the past history of a hot spot our thesis requires that we establish eruptions of granitic magma from its site as proof of its heated condition during an early stage, and that we show reason to infer continuance of the activity as a cause of orogenic movements into later periods. The diagrammatic map, Figure 8, shows the distribution of granites throughout the Archipelago and gives the geologic ages to which they are assigned, according to the relations as now known. The groups 1 to 9 were arbitrarily outlined by the senior author, and the ages were stated by Dr. Teiichi Kobayashi in a letter, quoted as follows:

Tokyo, April 26, 1939.

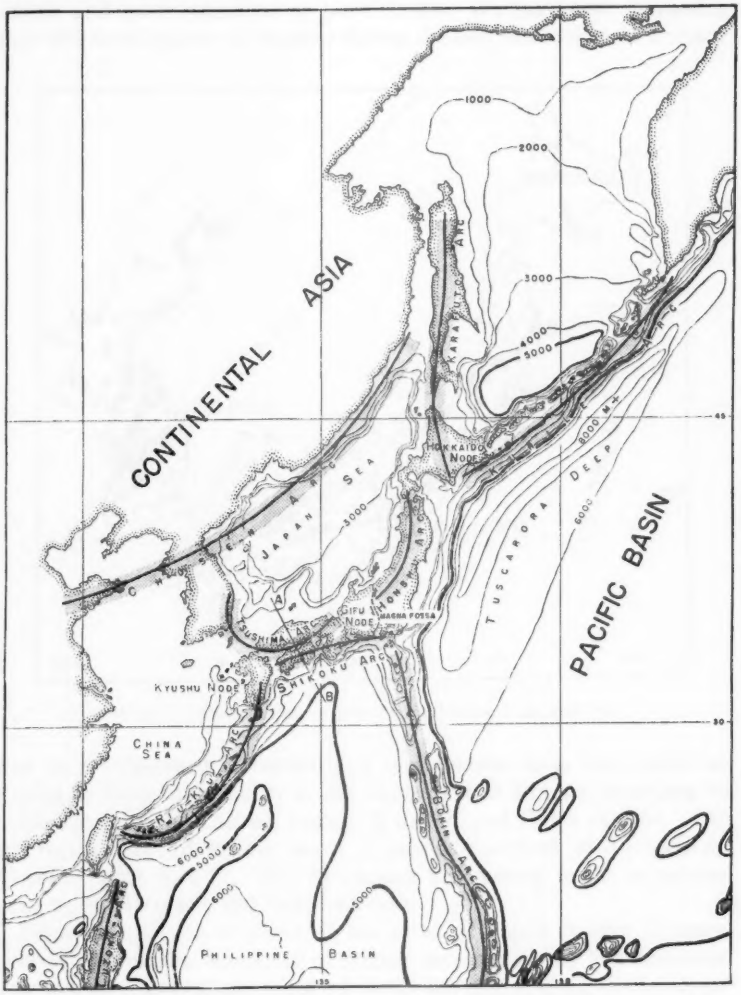
"As you most probably understand, it is rather difficult to determine the exact age of granites. In my opinion the plutonism in Japan may be classified tectonically into three series, the paleo-, meso-, and neo-plutonisms, which are related to the Triassic Akiyoshi orogenesis, the Jurasso-Cretaceous Sakawa orogenic cycle and the Neogene orogenic movements respectively.

"Referring to your map, parts of the granite in areas 3 and 5 probably belong to the paleo-plutonism, but the rest of the granite in those areas and the granites in areas 4, 7, and 8, and probably in 9 mostly belong to a later stage of the meso-plutonism. The granites in the 6 area may belong partly to the meso-plutonism and partly to the neo-plutonism.

"In addition to these autochthonous granites, there are exotic ones, which I call archae-granites. The exotic ones are found in the conglomerates of the Permian and Lower Triassic formations and, in my opinion, they are derived from the continent.

"The geologic history of Chosen (Korea) is quite different from that of the Japanese islands. There is the Pre-Cambrian Kokulian granite, but the paleo-plutonism has not as yet been established, although the Shoren orogenesis is a Korean equivalent of the Akiyoshi orogenesis. The meso-plutonism, on the other hand, was violent. The granite in areas 1 and 2 of your map belongs mostly to the Pre-Cambrian or else to the Cretaceous intrusion."

Dr. T. Kobayashi's dating of Japanese granites agrees with assignments of age by Professor Yabe of Sendai, particularly with reference



TECTONIC MAP OF THE JAPANESE ARCHIPELAGO

to the areas marked 6, 7, 8, and 9, in northeastern Japan. Both geologists place the major activity in the Lower Cretaceous, while not excluding earlier and later intrusions as possibilities. We may note in passing that this development of magmas during the late Mesozoic and Tertiary

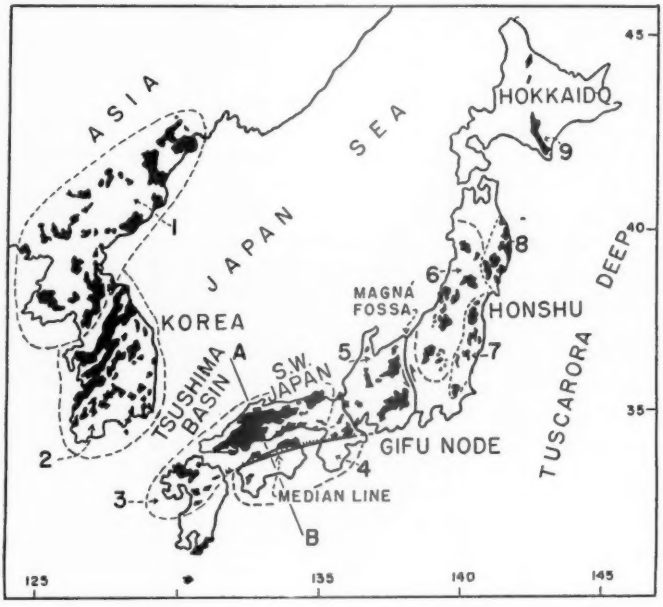


FIGURE 8.—*Distribution of granites in Japanese Archipelago*

was very widespread in eastern and southeastern Asia, from north of Peking to Hongkong, and from the Himalayas to Borneo, according to publications by the Chinese, Indian, Malayan, and Dutch surveys. For the region north of Peking one may consult the work of Teilhard de Chardin (1928, p. 6-7). The Philippines also belong to the structures built up by Mesozoic and later eruptions.

From the geologic relations of the rocks of Japan it thus becomes evident that notable intrusions of granite occurred during late Mesozoic time in a zone that extends from the peninsula, Korea, along the Japanese arc to Hokkaido on the north, encircling the southwestern and eastern sides of the Japan Sea Basin. The Basin was thus isolated from the Pacific in relatively late geologic time. Its earlier history and its origin as an element of the crust become of interest.

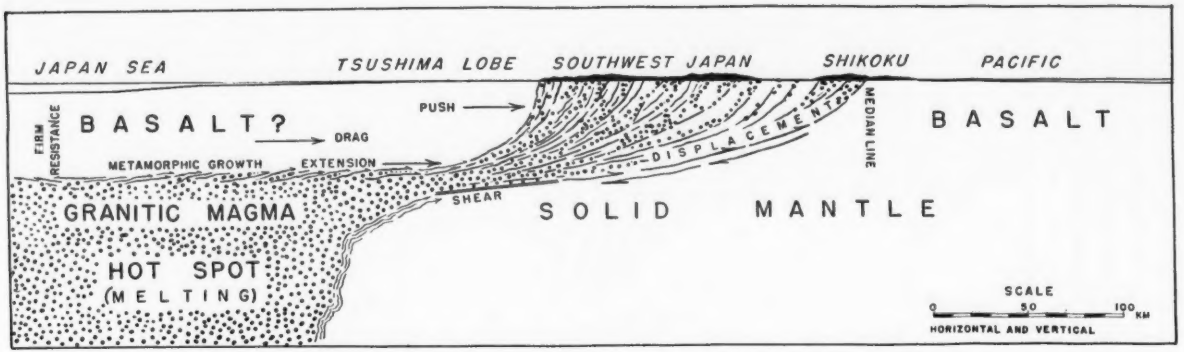


FIGURE 9.—*Hypothetical section through the orogenic mechanism of southern Japan*

The comparatively rounded form and smooth outline, devoid of projecting mountain ranges, suggest that the Japan Sea Basin is a simple unit. Its floor lies at oceanic depths, more than 3000 meters (10,000 feet) below sea level. Though no doubt covered by sediments of Tertiary, Mesozoic, and late Paleozoic age, it must have a basement of igneous rock, the character of which is indicated by the volcanoes that have been built up on it: the Oki group, Lat. 36° N., Long. 133° E., and the Utsuryoto, Lat. 37° 40′ N., Long. 131° E. According to the Geologic Map of Japan (1926) they consist of basalt and liparite. On these evidences we may infer that the structural element which corresponds with the Basin is a disc of basalt, similar to those which underlie the Pacific and comparable with the outflows of plateau basalts of India, Africa, and North America. If that be so, the mountain chain whose summits appear as the Japanese Archipelago takes its place as an example of a common type, built around the margin of a disc. The general mechanism, as we here identify it, consists of an extensive, discoidal layer of basalt, built up presumably by fissure eruptions during some epoch of Paleozoic or pre-Cambrian time and later framed by granitic bodies that rose around it. The granite is thought to have originated at some stage in connection with the basalt of the disc, as a product of remelting of a parent magma. Our essential postulate is that the granitic magma disturbed the stability of the crust in the manner described in preceding pages and that the elongation of the cover exerted pressure in a direction away from a firmer resistance toward a less resisting mass, with the result that the latter was pushed up in the form of the Japanese mountain chain (Fig. 9).

The general structure of the Japanese islands is consistent with this explanation. The Honshu Arc has been pushed eastward, the mass of the Gifu Node has been rotated in a clockwise direction, and southwestern Japan has been thrust southward. The general facts are confirmatory. For more detailed discussion the reader is referred to the article by Willis (1940).

CONCLUSION

In conclusion the student is invited to review the introduction, analyze the dynamics, frame the mechanism, and test the argument against the facts of orogeny.

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Box 1365, Stanford University, California; 406 W. 64 St., Inglewood, Calif.
Manuscript received by the Secretary of the Society, September 23, 1940.
Presented before the Cordilleran Section, April 12, 1940.

BULLETIN OF THE GEOLOGICAL SOCIETY OF AMERICA
VOL. 52, PP. 1685-1714, 2 PLS., 12 FIGS. OCTOBER 1, 1941

GRAVITY CORING INSTRUMENT AND MECHANICS OF SEDIMENT CORING

BY K. O. EMERY AND R. S. DIETZ

CONTENTS

	Page
Abstract	1686
Introduction	1686
Acknowledgments	1687
Coring device	1687
Construction	1687
Operation	1689
Results	1691
Factors controlling length of cores and depth of penetration	1691
General considerations	1691
Core-nose	1691
Core-tube	1693
Velocity and weight of corer	1695
Sediment character	1697
Core shortening	1699
General	1699
Loss from core-tube	1699
Compaction	1699
Slumping within core-tube	1701
Representation of only top layers of sediment	1701
Representation of all layers penetrated	1702
General	1702
Coring in layered sediment	1702
Hammering investigation	1704
Photographic study	1706
Sea-floor experiments	1706
Interpretation of experimental results	1711
Relation of shortening to study of core samples	1712
Summary and conclusions	1713
Works to which reference is made	1714

ILLUSTRATIONS

Figure		Page
1.	Coring device	1688
2.	Effect of length of core-tube and valve housing on core-length and penetration.	1695
3.	Effect of median diameter of sediment on core-length and penetration	1696
4.	Effect of sediment water content on core-length and penetration	1698
5.	Variation of water content with depth in cores taken in field operation	1700
6.	Experiment showing gradual increase in wall friction	1703
7.	Core-length vs. penetration curve obtained by dropping small-scale corers into layered clay	1704

Figure Page
8. Core-length vs. penetration curve obtained by hammering core-tubes into sediment 1705
9. Results of photographic study of five short cores 1707
10. Results of photographic study of two long cores 1708
11. Device for measuring core-length and penetration during the process of coring sea-floor sediments 1709
12. Core-length vs. penetration curve obtained under field coring conditions 1710

Plate Facing page
1. Coring device 1686
2. Core samples 1687

ABSTRACT

A gravity-type coring apparatus, which is used on the research vessel *E. W. Scripps* of the Scripps Institution of Oceanography for taking sediment samples of the ocean floor, is described. With this instrument more than 200 cores have been taken in many types of sediment. The 174 mud cores have an average length of 6 feet, 3 inches and a maximum length of 16 feet, 9 inches.

Data from a number of experiments and from field coring operations were analysed in order to improve the design of the device and to permit proper interpretation of core samples. A detailed study was made to explain the observation that the length of the cores averaged about 50 per cent of the depth of penetration of the core barrel. Laboratory coring experiments using mud of uniform water content show that, as the core barrel penetrates the mud, progressively smaller increments of core are added throughout the entire depth of penetration. However, studies of cores taken on a tidal flat and others obtained in field operations show that the size of core increments per unit of penetration remains practically constant with increasing penetration.

INTRODUCTION

During the year 1938, a number of problems connected with the geology of the Pacific Ocean floor off California were investigated by a group of geologists under the direction of Dr. F. P. Shepard. Early in the work, need developed for an inexpensive method of taking long cores in ocean floor sediments. In early investigations of ocean floor sediments, cores were obtained by using simple weighted tubes. Later instruments obtained their energy from exploding cannon powder (Piggot, 1936) or from the hydrostatic head of sea-water at the site of coring (Varney and Redwine, 1937). Modification of the simple and inexpensive gravity type resulted in the development of a large corer costing only about $100. Since 1938, a total of 229 cores having a maximum length of nearly 17 feet have been taken with this instrument from the research vessel *E. W. Scripps* off the coast of California and Mexico and in the Gulf of California.

It was noted that the core-length was commonly only 40 to 70 per cent of the distance of penetration of the core-tube. The method by which this shortening takes place should be known for proper interpretation

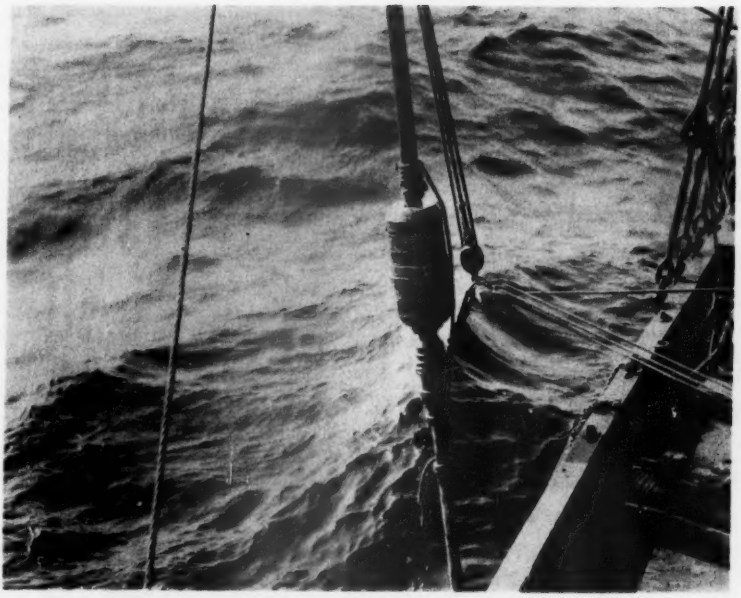

FIGURE 1. CORER OVERSIDE
Note method of handling with blocks and tackles. Photograph by Cliff Johnson

FIGURE 2 NOSES AND CORE-RETAINERS
From right to left: Core-retainer made by cementing strips of celluloid (with acetone) to another strip attached to a thin steel sleeve; core-nose and celluloid retainer for a 2.06-inch I.D. tube; thin rubber sleeve mounted on celluloid strips forming a complete core-retainer; core nose and retainer for 2.44-inch I.D. tube—containing a portion of a core; core-nose after encountering rock.

CORING DEVICE

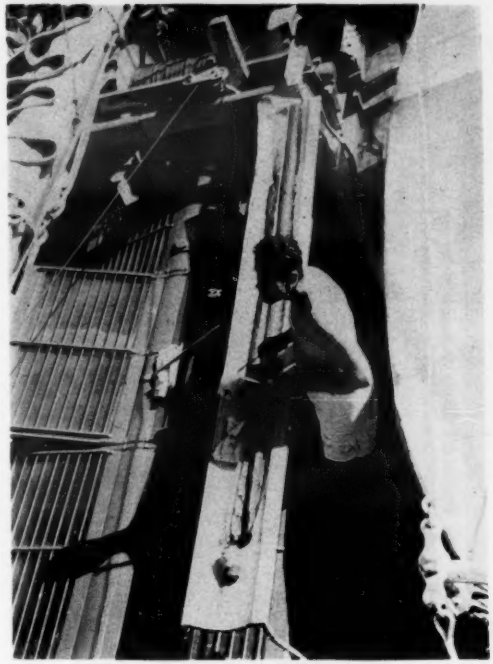

FIGURE 1. CORE ON SECTIONING TROUGH
The 15-foot core has been cut into two portions and while still in the opened celluloid core-liner is being sectioned and sealed in bottles.

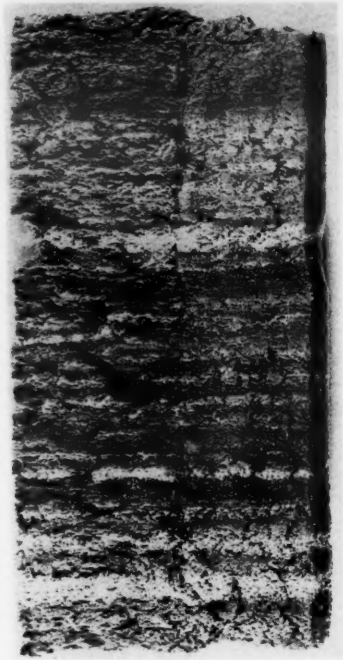

FIGURE 2. LAMINAE IN A PARTIALLY DRIED CORE OF DIATOM MUD FROM GULF OF CALIFORNIA
Note characteristic absence of disturbance.

CORE SAMPLES

of the cores. Accordingly, a number of experiments were undertaken to determine the factors which cause shortening and the manner in which it takes place.

ACKNOWLEDGMENTS

This investigation was made possible through the co-operation of the Geological Society of America, the Scripps Institution of Oceanography, and the University of Illinois. The use of the vessel *E. W. Scripps* permitted the collection of cores on a number of cruises off California during 1938 and on expeditions to the Gulf of California during 1939 and 1940.

The writers wish to express their especial appreciation to Dr. F. P. Shepard, at whose suggestion the corer was devised, and to Dr. Roger Revelle, who made available results of the laboratory study of the cores. Both Doctor Shepard and Doctor Revelle contributed ideas toward the construction and operation of the corer and also aided in the study of the results of experiments. Dr. M. Juul Hvorslev kindly read the manuscript and offered suggestions. Appreciation is also expressed to Mr. Carl Johnson of Scripps Institution who constructed the instrument, and to Capt. E. H. Hammond of the vessel *E. W. Scripps,* who devised a method of handling it on shipboard.

CORING DEVICE

CONSTRUCTION

Because core-tubes and noses, even though constructed of expensive alloy steel, usually are badly bent on striking rocky or sandy bottom, an effort was made to use common pipe and plumbing connections throughout. Rugged and simple construction reduced interruption of operations to a minimum.

The corer consists essentially of a shaft, weight, and core-tube (Fig. 1; Pl. 1, fig. 1). The shaft is a 2.44 inch I. D. standard pipe 8 feet long. Several small holes permit water to escape as the device is lifted from the sea. On the shaft is a series of nine 60-pound lead weights, roughly streamlined. The complete corer, weighing about 650 pounds in air, was operated with ⅜-inch wire cable on the large winch of the *E. W. Scripps.* Under some conditions, cores were taken with only enough lead attached to the instrument to give it a total weight of about 300 pounds. This lightened corer permitted the use of a smaller crew and only 3/16-inch wire cable.

Screwed onto the lower end of the shaft and forming a shoulder to take the thrust of the lead weights is a valve housing (Fig. 1) which consists of a short pipe 4 inches in diameter with a reducer at each end. Inside is a large rubber stopper, resting loosely in a brass seating. This valve

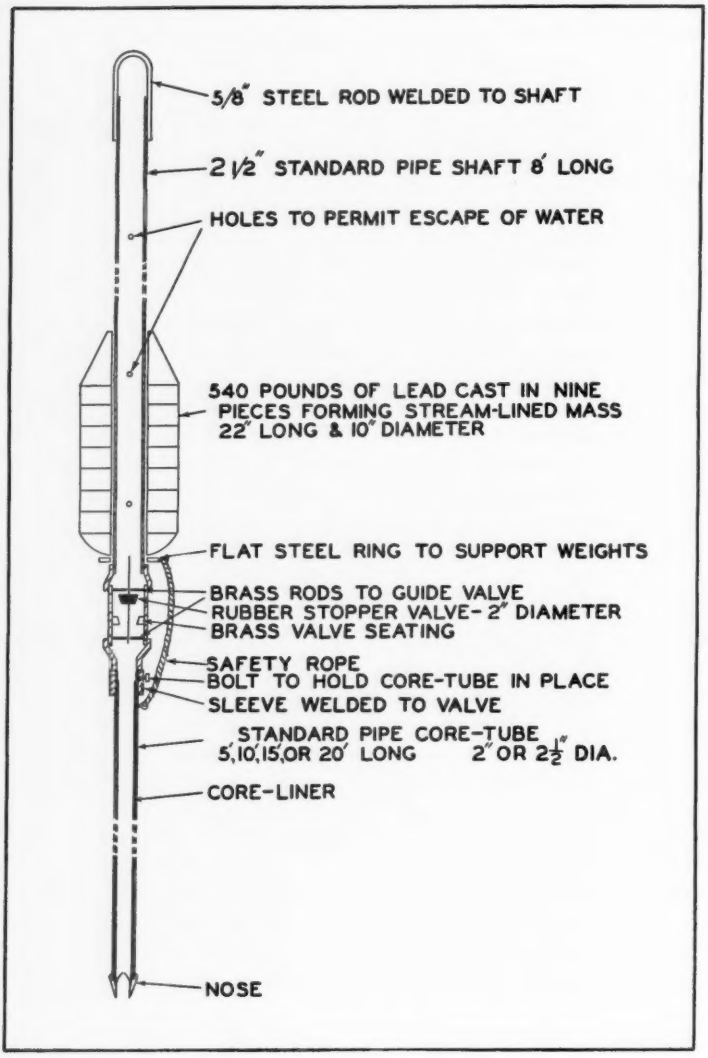
5/8" STEEL ROD WELDED TO SHAFT
2 1/2" STANDARD PIPE SHAFT 8' LONG
HOLES TO PERMIT ESCAPE OF WATER
540 POUNDS OF LEAD CAST IN NINE PIECES FORMING STREAM-LINED MASS 22" LONG & 10" DIAMETER
FLAT STEEL RING TO SUPPORT WEIGHTS
BRASS RODS TO GUIDE VALVE
RUBBER STOPPER VALVE- 2" DIAMETER
BRASS VALVE SEATING
SAFETY ROPE
BOLT TO HOLD CORE-TUBE IN PLACE
SLEEVE WELDED TO VALVE
STANDARD PIPE CORE-TUBE 5',10',15',OR 20' LONG 2" OR 2 1/2" DIA.
CORE-LINER
NOSE

FIGURE 1.—*Coring device*

prevents occasional loss of core by suction during withdrawal from the bottom, prevents washing out of the relatively fluid upper part of the core while the device is being hoisted through the water, and prevents the weight of the water column in the shaft from forcing out short cores after the instrument is lifted from the sea. Experiments showed that at the velocities used the valve does not inhibit the upward flow of water enough to influence appreciably the length of cores.

Below the valve is the core-tube, a 2.06 in. I.D. (2.38 in. O.D.) or a 2.44 in. I.D. (2.87 in. O.D.) standard pipe. Attachment is made by thrusting the tube into a sleeve and against a shoulder of the valve housing where it is clamped with a set screw. The lengths of core-tubes range up to 20 feet depending on the type of sediment expected. In recent work a removable core-liner has been placed inside the core-tube. This liner consists of a strip of 15-gauge celluloid reinforced at each end and rolled into a cylinder before being inserted into the tube. Its presence reduces the inside diameter of the core-tube approximately 0.04 inch.

Screwed to the lower end of the core-tube is a core-nose (Pl. 1, fig. 2) having an inside diameter ½ to ¼ inch less than that of the core-liner. Forming part of the nose is a core-retainer which consists of strips of celluloid thrust into a thin rubber sleeve. The strips of celluloid extend upward and inward from the core-nose (Pl. 1, fig. 2) in such a manner that during the entrance of a core they are pushed back against the tube wall. If the core starts to slip out, however, the strips close the opening, thus preventing further loss. The thin rubber sleeve makes the core retainer almost water tight—a requirement for the retaining of sand cores. This celluloid and rubber core-retainer proved far superior to numerous other types which were devised and tested.

OPERATION

After the instrument is assembled and lowered into the water (Pl. 1, fig. 1), it is dropped slowly until within about 300 feet of the bottom as indicated by the ship's echo sounding device and is then allowed to run rapidly with only a slight brake pressure to insure a vertical descent.[1] Velocities of 12 to 21 feet per second are attained just before striking bottom, regardless of the length of cable paid out. In depths shallower than 3000 feet a slackening of cable indicates that the instrument has hit bottom. Between depths of 3000 and 6000 feet, a pointer attached to an accumulator spring has been found useful, but at greater depths and in rough weather there is some difficulty in determining the instant

[1] An attempt to use wings or longitudinal vanes to aid the corer in maintaining a vertical position resulted in excessive fouling of the cable and proved unnecessary.

TABLE 1.—*Summary of Coring Results*

Type of sediment	Corer		No. of trials	Average core-length (inches)	Maximum-minimum core-length (inches)	Average penetration (inches)	Maximum-minimum penetration (inches)	Core-length to penetration ratio
	Approximate weight (pounds)	Diameter of tube (inches I. D.)						
Red clay	300	2.06	2	97 (1)*		135 (2)	132–138	73 (1)
Diatom mud	600 Emery-Dietz	2.44	23	156 (22)	48–201	>255 (23)	>152–>288	<63 (23)
	600 "	2.06	3	135 (2)	81–190	>134 (2)	>132–>136	<59 (2)
	250 "	2.44	9	87 (8)	48–147	121 (8)	72– 204	68 (7)
	250 "	2.06	13	66 (13)	38–116	126 (4)	96– 144	53 (4)
Green clayey or silty mud	600 "	2.44	7	104 (6)	49–180	>189 (7)	>106–>264	<53 (6)
	600 "	2.06	32	78 (30)	28–120	158 (29)	72–270	51 (23)
	250 "	2.44	10	66 (8)	49–85	106 (7)	81–132	60 (7)
	250 "	2.06	39	54 (37)	11–90	94 (20)	60–144	63 (15)
	150 (Ekman)	2.06 and 1.50	24	21 (24)	12–69	54 (17)	15–78	48 (17)
Sandy or shelly mud	600 Emery-Dietz	2.44	3	64 (3)	32–85	>158 (3)	>131–>180	<41 (3)
	600 "	2.06	40	52 (33)	20–91	>139 (36)	48–>186	41 (24)
	250 "	2.44	5	37 (5)	14–75	81 (4)	41–120	54 (4)
	250 "	2.06	11	32 (7)	15–64	38 (6)	24–48	51 (2)
	150 (Ekman)	2.08 and 1.50	5	12 (5)	7–20			
Sand, shells, or pebbles	600 Emery-Dietz	2.44	9	21 (7)	2–42	55 (7)	6–84	45 (6)
	600 "	2.06	38	21 (18)	4–65	57 (14)	18–115	41 (9)
	250 "	2.44	1	6 (1)		10 (1)		60 (1)
	250 "	2.06	33	16 (7)	6–23	37 (20)	11–65	72 (4)
	150 (Ekman)	2.06 and 1.50	12	5 (7)	3–15	8 (1)		
Gray clay Pre-Recent?	600 Emery-Dietz	2.44	9	15 (8)	4–42	30 (8)	6–75	43 (7)
	600 "	2.06	1	4 (1)				
	250 "	2.44	2	0		18 (2)	15–21	
Rock	600 "		16	— (6)				
	250 "		12	— (6)				
	150 (Ekman)		9	— (2)				

* The number of trials on which each average is based is indicated by the figure within parentheses.

of impact.[2] When bottom is reached, the winch is stopped immediately to prevent kinking of cable.

The undisturbed core is extracted from the core-tube by withdrawing and opening the celluloid core-liner (Pl. 2, fig. 1). Five-inch lengths of core are cut, scraped, described, and placed in mason jars or are sealed in cans.

RESULTS

Examination of Table 1 shows that for each type of sediment the longest cores were taken by the instrument having the greatest weight and the largest diameter core-tube. The average length of 22 cores of diatomaceous mud taken with the large corer is 13 feet. One of these cores is 16 feet 9 inches, and seven others are more than 15 feet long.

It will be noted that nearly 75 per cent of the misses resulted from the striking of sand or rock. In later work much better results for sandy sediments were obtained through the use of core-retainers. Data on a number of cores taken by a modified Ekman device (Trask, 1932, p. 11-13) are included in Table 1 for comparison.

The speed of operation is shown by the fact that as many as 11 trials have been made in a single day in water ranging from 50 to 400 feet in depth. Also, off Newport, California, four cores were taken from an average depth of 800 feet in about one hour. Operations in deeper water are somewhat slower, but the device has been used successfully at depths as great as 12,200 feet.

FACTORS CONTROLLING LENGTH OF CORES AND DEPTH OF PENETRATION

GENERAL CONSIDERATIONS

A number of factors control the length of cores, such as shape of the nose, diameter, wall-thickness, length of the core-tube, inner and outer wall-friction, weight of the corer, velocity of coring, and the character of sediment. Data on about 270 cores, taken in actual operations with various combinations of nose, tube, and weights, permit the evaluation of certain of these factors. A great deal of additional information came from numerous experiments in which coring velocity and type of sediment could be more easily controlled than in field operations.

CORE-NOSE

A number of experiments were made for evaluating the effect of the core-nose on the length of mud cores. Table 2 gives a comparison of core-

[2] A preliminary attempt was made to develop a mechanical sound emitting apparatus which, when attached to the coring instrument, would flash a signal to the ship's echo sounding device at the instant that the corer reached bottom. The attempt did not succeed, but it is probable that such an apparatus can be employed.

TABLE 2.—*Effect of nose in coring mud and stiff clay*

Stream bed; St. Joseph, Illinois, April 24, 1939

Sediment	Nose	Velocity (ft./sec.)	Weight (lb.)	Penetration (inches)	Core-length (inches)	Core-length/ penetration
Mud	without nose	11.4	31	13.5	11.3	0.84
Mud	with nose	11.4	31	15.3	10.3	.67
Mud	without nose	11.4	89	22.0	15.0	.68
Mud	with nose	11.4	89	25.0	18.5	.74
Mud	without nose	19.7	31	19.0	14.0	.74
Mud	with nose	19.7	31	23.5	15.8	.67
Stiff clay	without nose	40.0	31	15.0	9.5	.63
Stiff clay	with nose	40.0	31	20.5	18.8	.92

TABLE 3.—*Effect of core-nose in small-scale experiments with clay*

Scripps Institution, August 28, 1938

Tube	Nose I. D. (inches)	Nose O. D. (inches)
F (Flared-end)	0.71	0.83
S (Square-cut end)	.59	.68
T (Tapered end)	.49	.57

All tubes above nose have same diameter as nose of square-cut tube.

Tube	Velocity (ft./sec.)	Weight (lb.)	Penetration (inches)	Core-length (inches)	Core-length/ penetration
S	13.8	1.4	4.8	1.9	0.40
T	13.1	1.5	4.6	3.2	.70
S	7.9	10.9	11.6	3.2	.28
T	7.9	10.9	11.2	3.6	.32
F	7.9	7.8	11.1	2.8	.25
S	7.9	7.8	9.2	3.2	.35
T	7.9	7.8	10.8	3.2	.30
F	6.6	7.8	10.4	2.6	.25
S	6.6	7.8	8.1	2.6	.32
T	6.6	7.8	7.4	2.7	.37
F	4.6	10.9	9.8	2.4	.24
S	4.6	10.9	9.5	3.0	.32
T	4.6	10.9	9.2	3.4	.37

lengths obtained in experiments in mud using a 2.06 inch I.D. core tube alternately with and without a nose (1.87 in. I.D.) attached. It will be noted that the use of the nose (Pl. 1, fig. 2) generally resulted in a longer core and a greater penetration. A longer core also was obtained

TABLE 4.—*Effect of nose in coring sand*

Scripps pier, August 24, 1939

Velocity (ft./sec.)	Weight (lb.)	Tube Diameter (inches I.D.)	Nose I. D. (inches)	Penetration (inches)	Core-length (inches)	Core-length/penetration
13.8	30	2.06	no nose	7.0	6.7	0.96
19.6	30	2.06	no nose	8.7	8.0	.92
21.9	30	2.06	no nose	9.2	8.7	.95
13.8	30	2.06	1.94	6.8	4.9	.72
19.6	30	2.06	1.94	9.0	7.0	.78
21.9	30	2.06	1.94	9.5	8.5	.89
13.8	30	2.06	1.82	4.7	3.4	.72
19.6	30	2.06	1.82	6.7	4.6	.69
21.9	30	2.06	1.82	8.6	5.4	.63
20.4	25	1.62	no nose	9.1	7.3	.80

when a nose was used on tubes hammered into mud (Fig. 8). Smaller scale experiments made with glass tubing also produced similar results (Table 3).

Judging from the experimental results, it seems that the core-nose has two main functions: it permits the taking of longer cores and it allows greater penetration[3] in mud (Pratje, 1935, p. 26). The mud column passing through the nose has a diameter slightly less than that of the tube wall. This allows the core to pass upward with less friction against the wall than would be the case were no nose used. Similarly, the larger outer diameter of the nose causes a thrusting aside of the mud so that it does not drag so much on the surface of the pipe. In contrast to this action for mud, other experiments indicate that longer sand cores are obtained if no nose is used (Table 4).

CORE-TUBE

In order to evaluate the effect of the core-tube diameter, a series of cores was taken in the muddy bottom of a recently diverted stream. The results are shown in Table 5. It will be noted that the ratio of core-length to penetration increases and that the penetration decreases

[3] The depth of mud smearing on the outside at the core tube is taken as a measure of the penetration. Due to the slight downward deflection of mud below the core-nose, this is not an exact measure of the thickness of mud penetrated but serves as a close approximation.

progressively with increasing tube diameter even though the larger tubes were heavier. As the diameter increases from 0.60 inch to about 2.44 inches, the core-length also increases. In these experiments no gain in core-length was obtained through the use of core-tubes larger than 2.44

TABLE 5.—*Effect of tube diameter, velocity, and weight*

St. Joseph, Illinois. April 9, 1939

No nose

Sediment	Velocity (ft./sec.)	Weight (lb.)	Tube I. D. (inches)	Penetration (inches)	Core-length (inches)	Core-length/penetration
Mud—33% water	11.4	19	0.60	19.5	6.0	0.31
	11.4	21	0.82	19.0	7.5	.39
	11.4	24	1.03	18.0	9.0	.50
	11.4	23	1.37	12.5	9.2	.74
	11.4	31	2.06	13.5	11.2	.83
	11.4	37	2.44	12.0	11.5	.96
	11.4	30	3.07	10.0	9.5	.95
	19.7	19	0.60	26.5	3.5	.13
	19.7	21	0.82	30.5	11.8	.39
	19.7	24	1.03	26.0	14.2	.55
	19.7	23	1.37	20.5	14.0	.68
	19.7	31	2.06	19.0	14.0	.74
	19.7	37	2.44	17.2	15.5	.90
	19.7	30	3.07	17.0	15.5	.91
Stiff clay 34% water	11.4	31	2.06	7.8	5.2	.67
	40.0	31	2.06	15.0	9.5	.63

inches. In operations at sea, cores obtained with the 2.44-inch core-tube averaged about 25 per cent longer than those taken with the 2.06-inch tube (Table 1).

A factor affecting penetration which has often been neglected is the length of the core-tube. In order to test the effect of core-tube length, data from all corings were plotted (Fig. 2). The diagonal line indicates the locus on which the points would lie if the instrument had penetrated just to the bottom of the weights, immersing both the core-tube and the valve in the mud. Fifty-six of the 187 points lie below this line, and also fairly close to it, suggesting that many of the penetrations were shortened by the plunging of the weights into the mud. In order to avoid this braking effect longer core-tubes should have been used.[4]

Friction of the sediment against the inside of the core-tube is also a factor controlling core-length. Cores taken in experiments using celluloid

[4] Two tests using 30-foot core barrels were made in recent work, but unfortunately only sections of 2.06 (i.d.) pipe were available. Pipe of this diameter was not strong enough to resist bending, and consequently both trials failed.

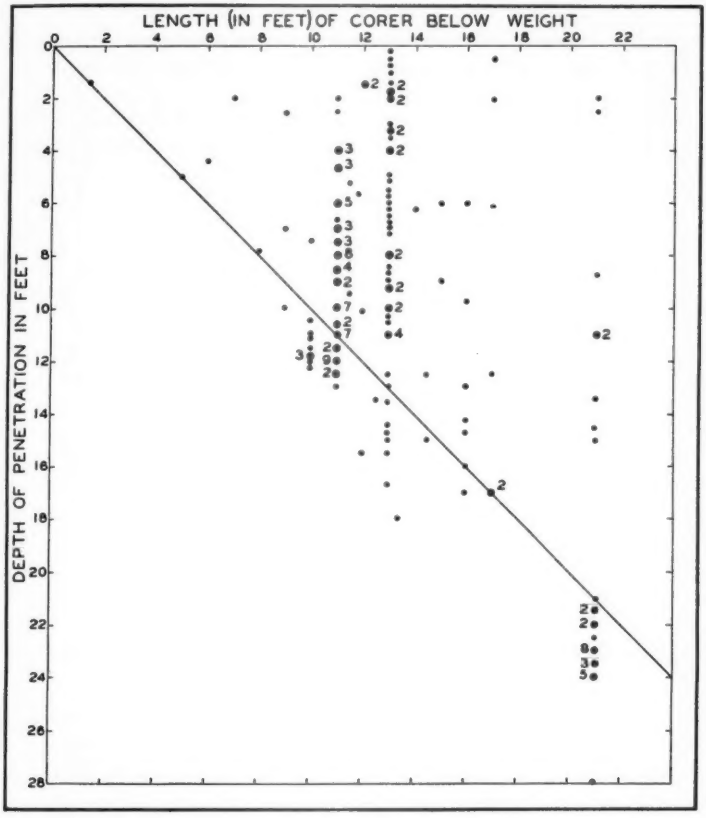

FIGURE 2.—*Effect of length of core-tube and valve housing on core-length and penetration*

Large dots and adjacent figures show position and number of coinciding tests. Braking of the weight as it plunges into the sediment retards further penetration.

liners were slightly longer than others taken in the absence of a smooth liner.

VELOCITY AND WEIGHT OF CORER

Both increased weight and increased velocity were found to be important in obtaining longer cores and deeper penetrations (Tables 1-6). The ratio of core-length to penetration was usually slightly lower with higher velocities. However, cores taken by the Varney-Redwine hydraulic apparatus as well as others taken in experiments on land with the Piggot

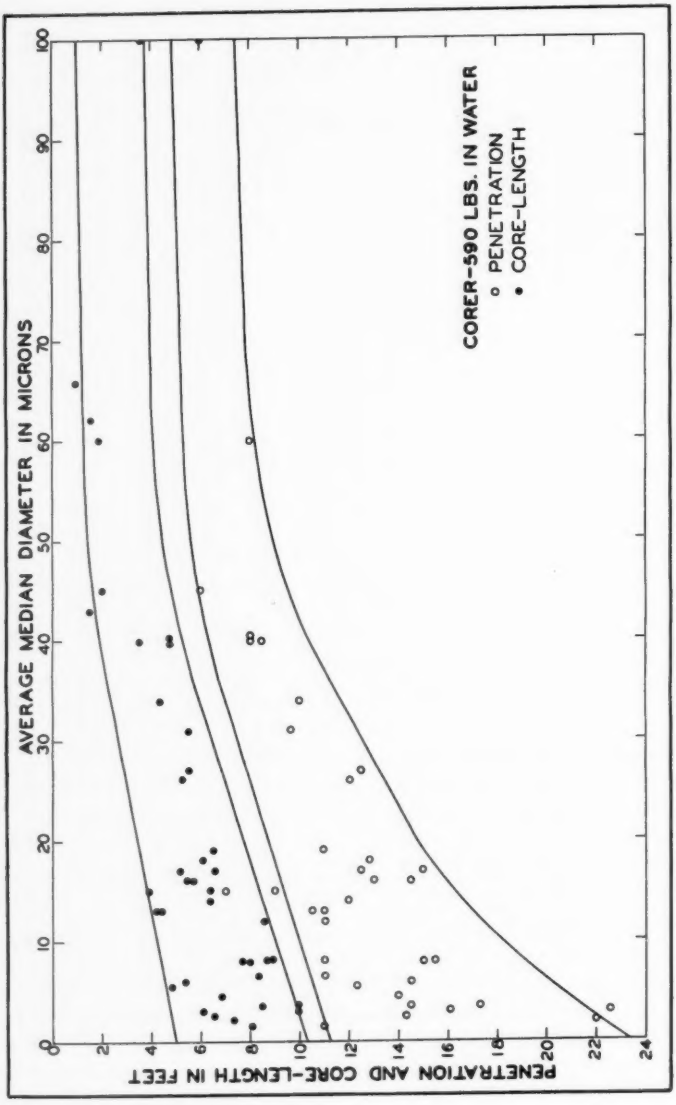

FIGURE 3.—*Effect of median diameter of sediment on core-length and penetration*

Note that, in general, longer cores (shown by dots) and deeper penetrations (circles) are obtained in finer sediments.

explosive type show a similar ratio to that found in the present writers' work (L. E. Redwine and C. S. Piggot, personal communications).

SEDIMENT CHARACTER

Study of coring data indicates that one of the most important factors influencing core-length and depth of penetration is the character of the

TABLE 6.—*Effect of weight and velocity in coring mud*

Stream bed, St. Joseph, Illinois, April 9, 1939
No nose

Velocity (ft./sec.)	Weight	Tube I.D. (inches)	Penetration (inches)	Core-length (inches)	Core-length/ penetration
11.3	31	2.06	13.5 13.0	11.3 11.3	0.84 .87
11.3	89	2.06	22.0	15.0	.68
19.7	31	2.06	19.0	14.0	.74
19.7	49	2.06	33.5 30.0	21.0 20.0	.63 .67

sediment. Such properties as medium diameter, water content, sorting, mineralogy, and grain shape appear to be significant. Sediments encountered by the Meteor Expedition, listed in the order of increasing core-length are: sand, diatom ooze, pteropod and globigerina ooze, hemipelagic and glacial-marine mud, and red clay (Pratje, 1935, p. 24). Excepting diatom ooze it will be noted that longer cores were obtained from finer-grained sediments. Pratje considered diatom ooze a special case because of the feltlike texture formed by the interlocking lath-shaped grains.

Sediments which were sampled off California and in the Gulf of California may be classified into five main groups: sand, sandy mud, silty or clayey mud, diatomaceous mud, and red clay. Table 1 shows that both the average core-length and the average penetration are greater for finer sediments. The ratio of core-length to penetration is also greater for finer sediments. Figure 3, based on sediment analyses made by Revelle, bears out the conclusion from field data that there is at least a rough correlation between the coring properties of sediments and their grain size.

The coring properties of sediment are also closely related to their water contents. (Compare Figures 3 and 4.) In each of about a hundred cores examined, the water content was found to be lower at the bottom than at the top of the core (Fig. 5). (*See also* Bramlette and Bradley, 1940,

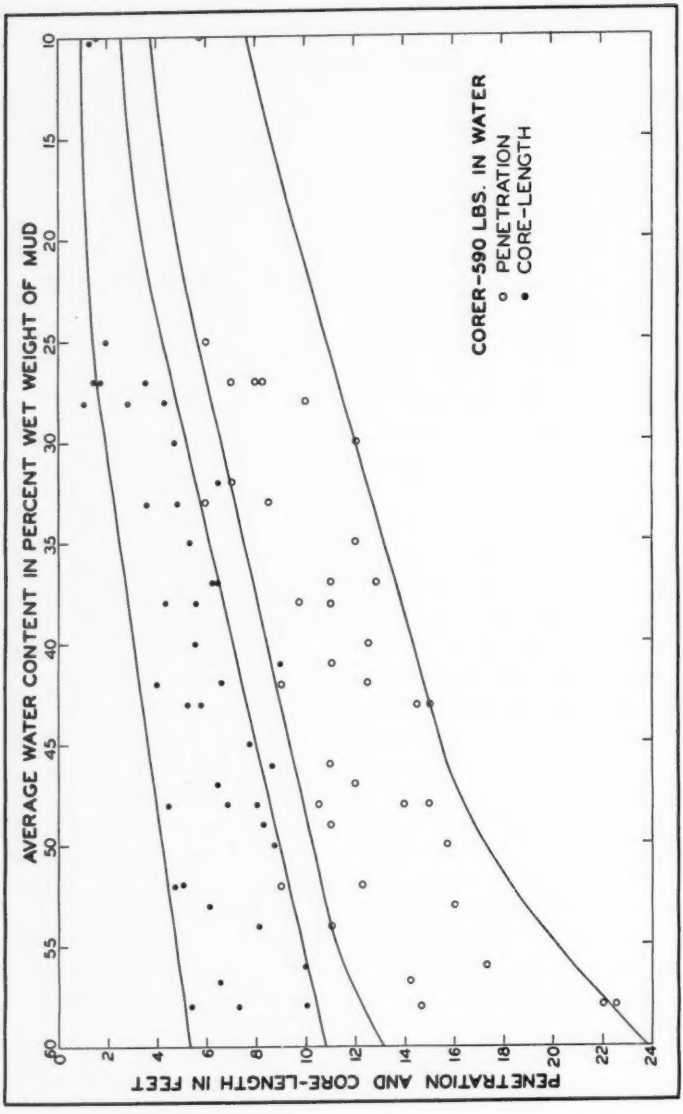

FIGURE 4.—*Effect of sediment water content on core-length and penetration*

Note that longer cores (shown by dots) and deeper penetrations (circles) are obtained in sediment of higher water content. *Compare* with Figure 3.

p. 27, for similar data on Atlantic cores.) The only exceptions were those in which the sediment at the core bottom was much finer-grained than that nearer the top of the core. This variation may be of considerable significance as will be pointed out later.

CORE SHORTENING

GENERAL

For most marine cores on which complete data are available, the core-length ranges from 40 to 70 per cent of the depth of penetration. It is obvious that an understanding of the manner by which this shortening occurs must be obtained in order to correlate layers of sediment. The manner of shortening also bears on the interpretation of physical properties of samples at various depths in cores.

LOSS FROM CORE-TUBE

A few cases of shortening can be explained by partial loss of the sample during or after withdrawal of the corer from the sediment. This is more likely to occur with cores of sand than with finer sediment (Table 1); however, careful checking of the inside of the core-tube or core-liner above many cores of mud showed that no slipping had occurred. Also, in a number of the later field operations a core retainer placed in the nose (Pl. 1, fig. 2) automatically closed after the core had been taken, thus preventing loss by slipping. Shortening still occurred to the same extent as when this retainer was not used.

Since the lengths of all experimental cores taken on land were measured before withdrawal of the instrument from the sediment, the possibility of slipping was eliminated. Yet, each of about 150 such cores were shorter than the distance of penetration.

COMPACTION

It is conceivable that the shortening might be due to compaction resulting from the escape of water (Wrath, 1936; Bramlette and Bradley, 1940, p. 27). If this occurred, however, it would seem that traces of channels of escape of the water might be left in the core, but none has been noted. Furthermore, laboratory experiments indicate only a slight decrease in water content of the core over that of the undisturbed sediment. For example, a core was taken in a box of artificially colored clay layers having an original water content of 54.4 per cent by volume (Table 7). The average water content by volume for the entire core sample was 53.0 per cent; hence, the core-length should have been 97 per cent of the penetration if shortening were due only to compaction or loss of water.

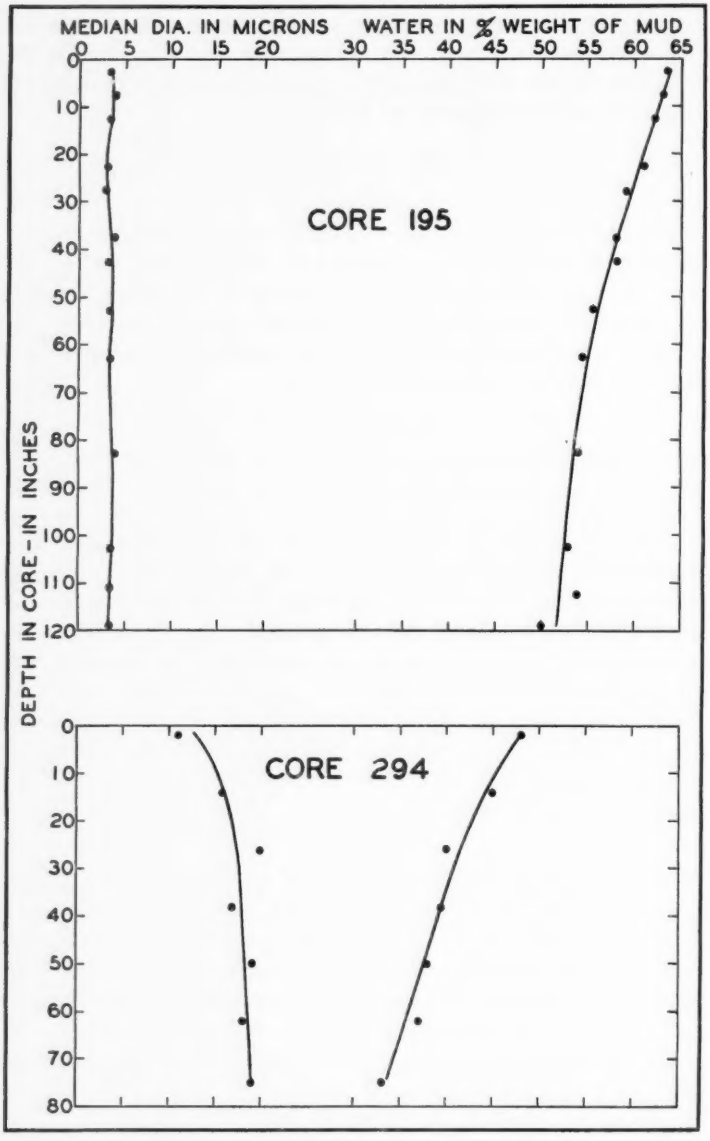

FIGURE 5.—*Variation of water content with depth in cores taken in field operation*
Note vertical gradient of water content which exists even though grain-size is relatively constant.

Actually, the core-length was only 30 per cent of the penetration; therefore, some other factor was much more important than compaction.

The idea has sometimes been expressed that the shortening is due to compression. However, this is obviously a loose use of the word *compression* (change in volume of a given mass in response to pressure) in place of *compaction* (change in volume due to loss of water).

TABLE 7.—*Water content of core taken through layers of colored clay of equal water content*

August 28, 1938

Depth in core (inches)	Depth of penetration (inches)	% wet weight	Water content % wet volume
0–1	0–1	32.3	54.4
1–2	1–2	31.2	53.2
2–3.4	2–11.4	29.9	51.8

SLUMPING WITHIN CORE-TUBE

Hvorslev (personal communication) has found that slumping or lateral expansion of soft material until it fills the core-tube is a factor causing shortening of soil samples. Probably some of the difference between the depth of penetration and the length of sea-floor cores is due to the same cause. When the inner diameter of the nose is 1.87 inches and that of the core liner is 2.02 inches, complete slumping would reduce a core to 86% of its original length. Similarly, the 2.06 inch nose with the 2.40 inch core liner would produce a core 74% as long as the original. Judging by the fact that core-length to penetration ratios average about 50% (Table 1), slumping is not the major cause of the shortening. Note also that the core-length to penetration ratio is low even when no nose is used and no opportunity to slump is presented (Figs. 7-10; Tables 2, 3, 5, 6).

REPRESENTATION OF ONLY TOP LAYERS OF SEDIMENT

Core samples are usually interpreted as though they consisted of only the undeformed top layers of sediment penetrated (Schott, 1935; Bramlette and Bradley, 1940). However, if this were true, it would follow that the inside of the core-tube exerts absolutely no resistance to the passage of a cylinder of mud until the core reaches a certain length, after which the resistance instantaneously becomes so great that the core cannot be pushed farther up the tube.

In order to learn something of the manner by which this internal resistance is built up, experiments were made in mud using a 2.06-inch (i.d.) core-tube. It was found that the length of the core could be increased

by withdrawing the tube from the mud and, without removing the core, dropping it back again. Increments were added for each of 11 trials, at the end of which the total core was twice the length of the original and nearly twice the average depth of the individual penetrations (Fig. 6). While not directly comparable to actual coring processes, this experiment shows that resistance toward movement of the core becomes gradually and not suddenly greater as the core becomes longer. Thus it seems impossible that there could exist a stage of no resistance during which the core would be taken, followed by a stage of high resistance when no more core could enter the tube.

REPRESENTATION OF ALL LAYERS PENETRATED

General.—As pointed out by Hvorslev (1940, p. 17) and as shown in Figure 6, a point may be reached where the resistance toward movement of a core becomes so great that further penetration causes only a pushing aside of sediment at the core-nose. There is some question, however, whether this point is reached during the course of ordinary coring operations.

It is obvious as shown above that increments must still be added to the core after the instrument has penetrated the sediment to a depth greater than the length of the core. However, for the proper interpretation of core samples, it is necessary to know whether there are new core increments throughout part of the remaining distance of penetration or throughout all of it. Similarly, it is desirable to know something of the relative size of the increments added to different portions of the core. Both of these problems were investigated by a number of methods.

Coring in layered sediment.—The problem of shortening may be solved by a comparison of layers in the core with the same layers in the undisturbed material. In the absence of Recent varved clays, some experiments were made in crudely stratified material consisting of 16 inches of mud at the top, 20 inches of mud high in organic debris in the middle, and cleanly washed sand at the bottom. All cores penetrating a given layer contained some material from that layer even though the core-length itself were less than the depth of burial of the top of the layer. Variation in the coring properties of the different layers prevented the making of interpretations regarding the size of increments added to the core during the penetration.

Less comparable to actual coring operations, but still significant, is a series of experiments in which weighted glass tubes of 0.59-inch inner diameter were dropped into a box of layered clay having a uniform water content. Eleven artificially colored clay layers, each one inch thick, were

present. Of 53 cores in which no observed loss had occurred only 6 failed to include the layer in which the tip of the corer had stopped. Since the average penetration into this layer was only 0.24 inch, the absence of

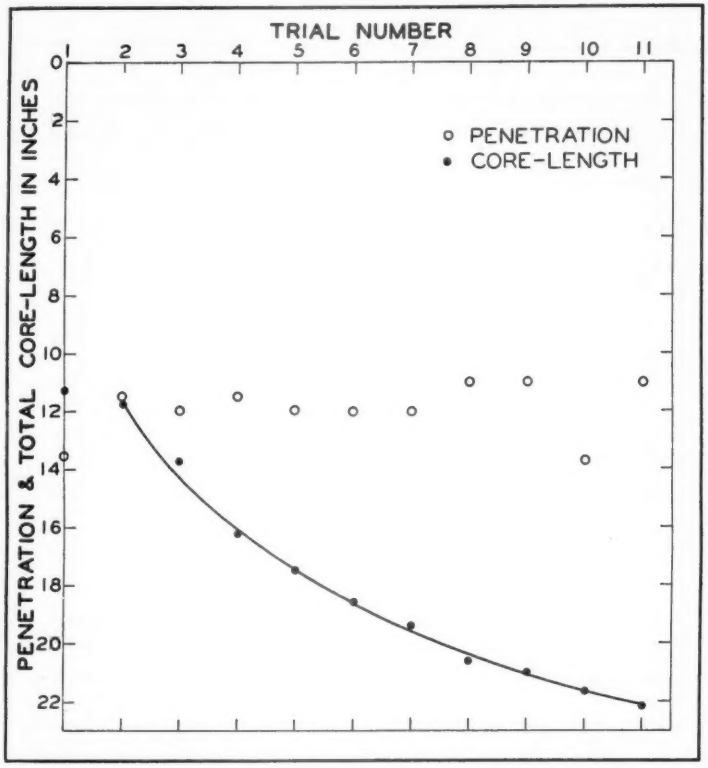

FIGURE 6.—*Experiment showing gradual increase in wall friction*

A 206-inch I.D. core-tube was dropped into mud 11 times from same height. After each trial, core was measured but not removed from tube. Note effect or total core length on size of increments. Experiment at St. Joseph, Illinois, stream channel, April 9, 1939.

the bottom layer may have been due to very slight slipping of the core when the tube was extracted or, more likely, to down-bending of the layers slightly in advance of the corer. In these small scale cores, the top layer was represented in its full thickness, and each successive lower layer was progressively thinner (Fig. 7) so that the average core-length was only 40% of the penetration.

Hammering investigation.—While a core-tube is being hammered or pushed into sediments the length of the core and the distance of penetration may be measured at frequent intervals. A test using this method was made on a tidal flat, where three cores were taken with penetrations

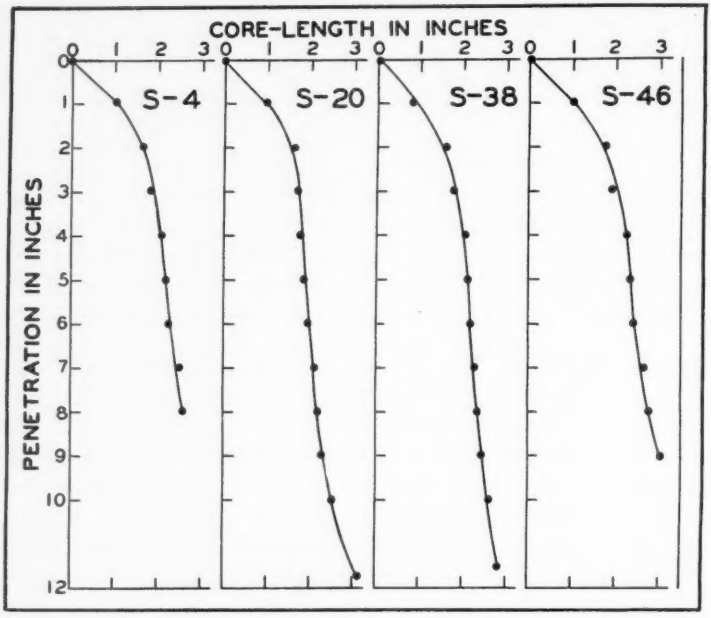

FIGURE 7.—*Core-length vs. penetration curve obtained by dropping small-scale corers into layered clay*

Note that smaller increments are added as core becomes longer. No nose. August 28, 1938.

of 7 to 8 feet. Two thin-wall 2-inch (1.91 in. I.D.; 2.02 in. O.D.) pipes without noses and one standard 2-inch (2.06 in. I.D.; 2.38 in. O.D.) pipe equipped with a nose (1.88 in. I.D.) were hammered into mud. Examination of Figure 8 shows that increments of approximately the same size were added to the cores along the entire distance of penetration in spite of the variable nature of the sediment.

On the other hand, in a similar test which consisted of hammering a 45 mm. diameter core-tube into mud, Pratje (1934) found evidence of a lack of continuous addition of core increments toward the bottom of the penetration. The sediments involved, however, seem to be unusual in

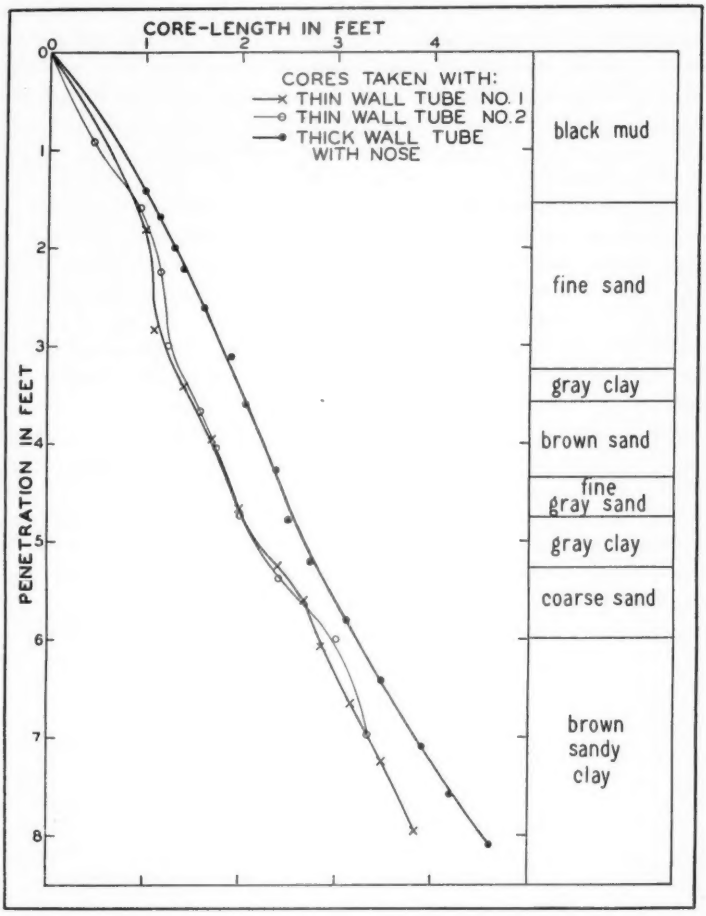

FIGURE 8.—*Core-length vs. penetration curve obtained by hammering core-tubes into sediment*

Note that cores taken with thin wall tubes, having no nose attached, were more influenced by sediment character than those with thick wall tube, equipped with a nose. October 1938.

that the water content ranged progressively from 51% at the surface to 68% at a depth of 4 meters. This variation suggests that the deeper material was more mobile and thus could be easily pushed aside at the core-nose.

Photographic study.—A photographic method of comparing core-length with penetration was attempted in an effort to learn something of coring mechanics while experimenting under conditions similar to those of actual coring operations. A light rod with a foot, or pad, at the lower end and a cross-piece at the upper end was placed inside a 2.06 in. I.D. core-tube. The rod was just the length of the core-tube, and in the starting position the cross-piece rested on top of the vertical tube. When the core-tube was dropped into mud, the bottom of the rod remained on the surface of the mud core; accordingly, the length of rod extending above the core-tube could be used as a measure of the length of the core. Similarly, the length of the core-tube projecting above the ground surface could be employed as a measure of the depth of penetration. By use of a movie camera, the positions of the core-tube and of the cross-piece of the rod were photographed at short time intervals. Later, the images were measured on a screen on which the film was projected.

Five experiments, made with a relatively light apparatus on a tidal flat near San Diego, California, were photographed in this manner. In two of these cores, increments were added along the entire distance of penetration. In one experiment, however, apparently no core was added in the last 10 per cent of the penetration. In the two other trials the apparent length of the core decreased at the bottom of the penetration, probably because the rod drove down into the top of the core. The data from these experiments are shown in Figure 9. It will be noted that, except near the bottom, equal increments were added per unit of penetration and not smaller increments as in the small-scale experiments with the glass tubes.

Two other cores, 4 feet long with penetrations of about 7 feet, were taken near the site of the previous experiments, using a much heavier instrument. In both of these tests the ratio of core-length to penetration remained nearly constant throughout the length of the core, but the penetration per unit of time and likewise the core recovery gradually decreased to zero during the last quarter of the coring time interval (Fig. 10). It should be noted, however, that the velocity of the apparatus (penetration per unit of time) actually increased for the first 0.4 of a second because of the excess of gravitational acceleration over the resistance offered by the mud. In this respect the conditions of the experiment were not quite analogous to those of actual coring operations.

Sea-floor experiments.—The above data were derived from experiments made on land; therefore, it became desirable to obtain similar information for cores taken at sea. A relatively simple device for measuring and recording the core-length and penetration at a number of points for each

core was constructed (Fig. 11). Essentially, it consists of a core-tube, a plunger, and a rider. The tube is a 2.06-inch pipe with a ⅛-inch slot milled down one side. The opposite side has screw heads mounted on the outside at 4-inch intervals. The plunger is a cylindrical paraffin-coated

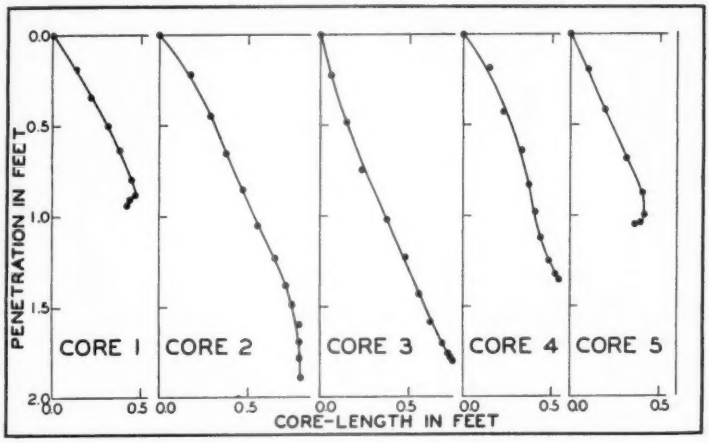

FIGURE 9.—*Results of photographic study of five short cores*

Experiments at Mission Bay, California, using 30- to 80-pound 2.06-inch I.D. core-tube dropped from a height of 3 to 5 feet. Each dot represents a photographic exposure. No nose. August 1939.

stick with disk guides at each end to center it in the tube and permit it to slide freely inside. Fitted to slide along the outside of the tube is a rider so constructed that contact with each screw head of the tube causes a pointer extending through the slot of the tube to cut momentarily into the paraffin coating of the plunger.

In operation, the instrument was dropped slowly to the bottom. While the tube drove down into the mud, the rider stopped at the mud surface, and the plunger remained just above the core. Each screw head of the tube as it passed through the rider caused a notch to be cut in the plunger. If the plunger itself were stationary with respect to the core-tube (that is if no core were taken) the notches in the paraffin would be 4 inches apart. On the other hand, if the core rose inside the tube as rapidly as the tube penetrated the mud (because of no shortening) all the notches would be superimposed. Accordingly, successive notches in the paraffin indicate 4-inch increments of penetration, and the distance between them is equal to the difference between the increment of penetration, 4 inches, and the increment of core. Thus, measurement of the distances between the

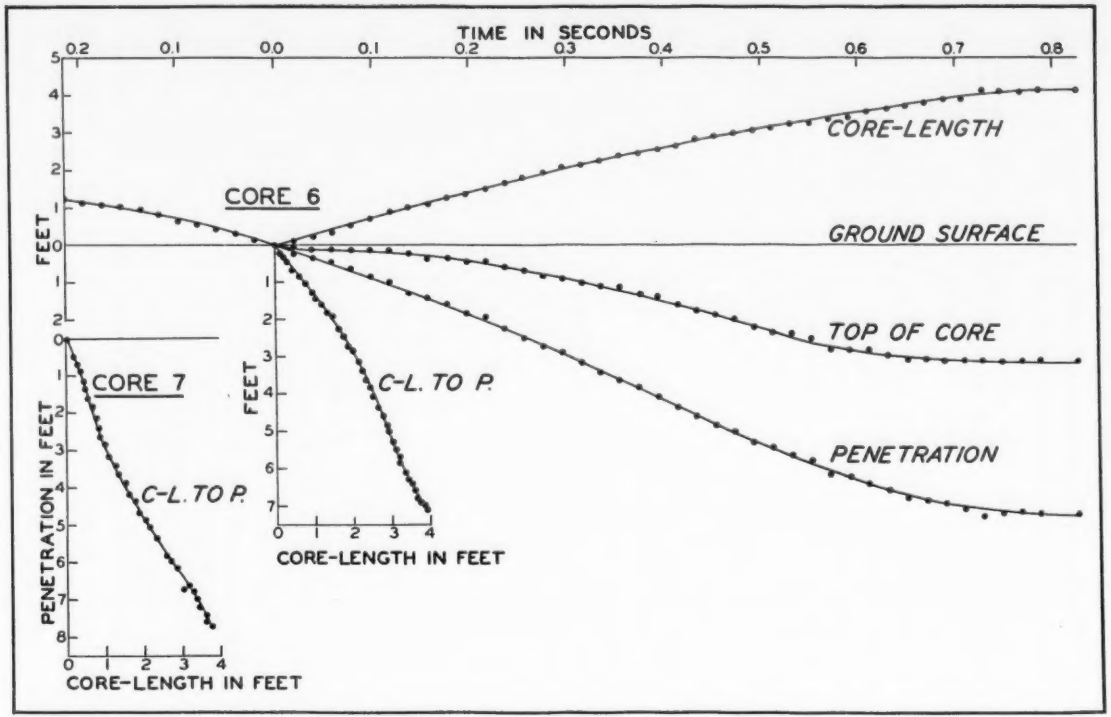

FIGURE 10.—*Results of photographic study of two long cores*

Experiments at Mission Bay, California, March 16, 1940, using 170-pound 2.06-inch I.D. corer dropped from a height of 1.2 and 1.8 feet. No nose. Top curve shows increase of core-length with time. Lower curves show position of top of core and increase in depth of penetration with time. Note that core-length vs. penetration curves of both cores are reasonably straight lines. (*Compare* with Figure 9.)

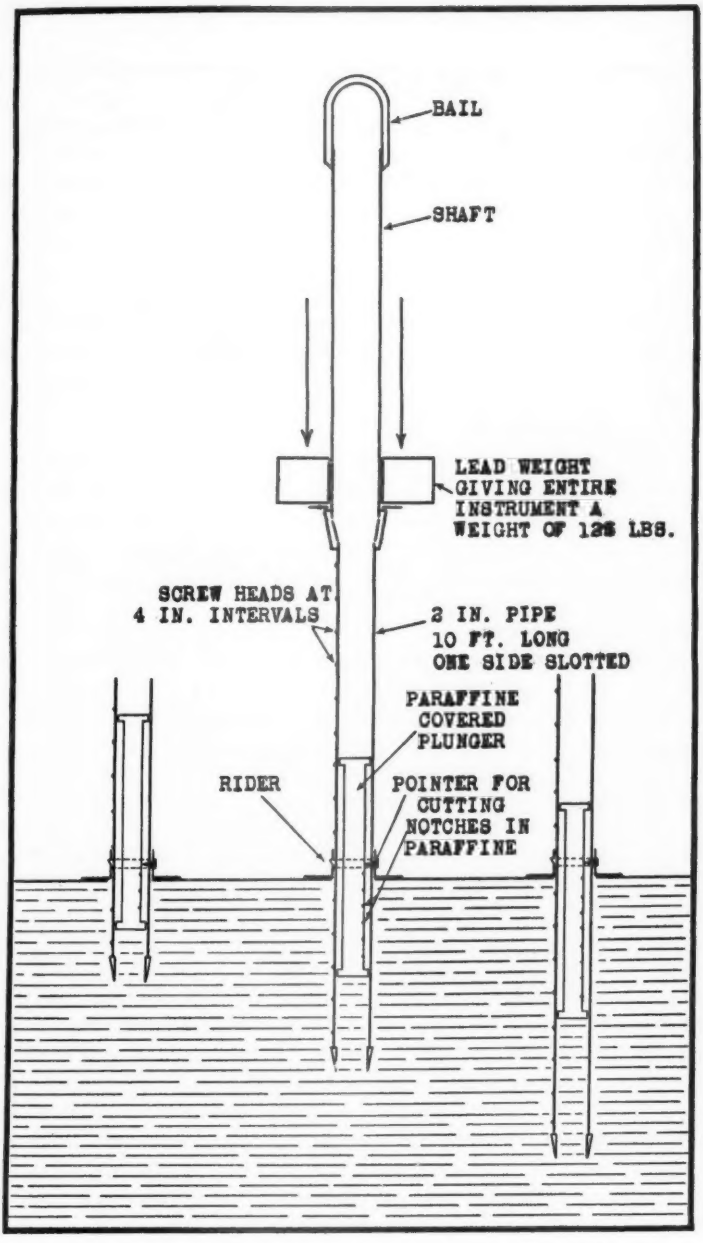

FIGURE 11.—*Device for measuring core-length and penetration during process of coring sea-floor sediments*

Three successive stages are shown.

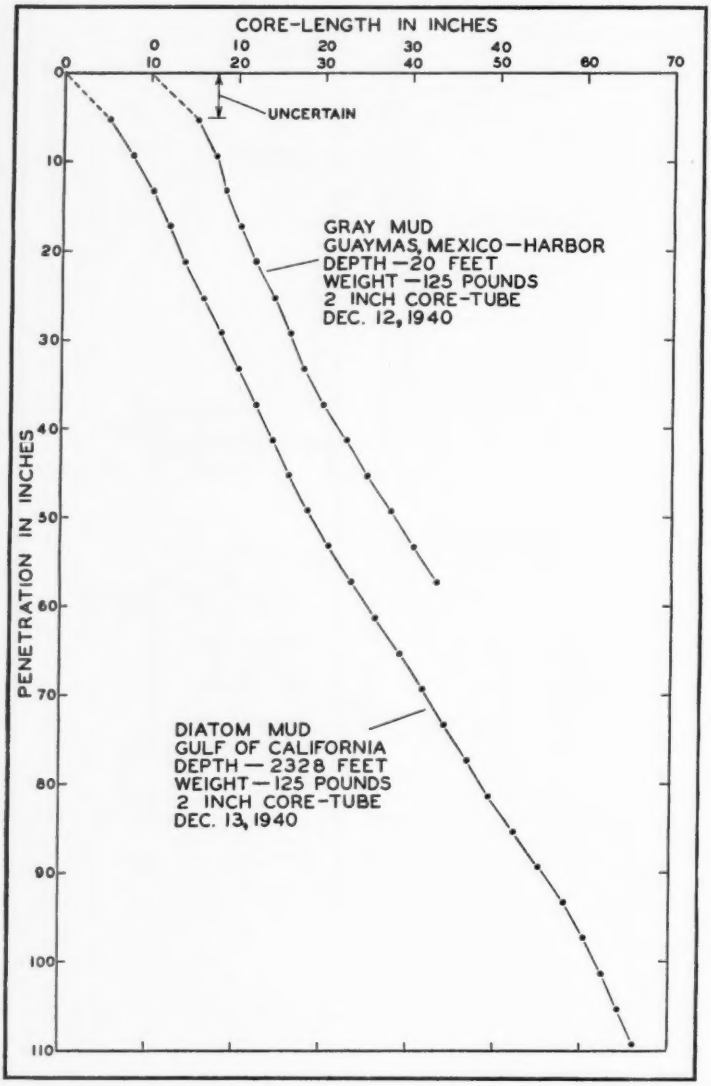

FIGURE 12.—*Core-length vs. penetration curve obtained under field coring conditions*

Nose attached. December 12 and 13, 1940, Gulf of California.

notches of the plunger provides enough information for the construction of a core-length to penetration curve.

The instrument was used in gray mud in Guaymas Harbor, Mexico, at a depth of 20 feet. This trial resulted in a 33-inch core with a 57-inch penetration. Figure 12 shows that the core-length to penetration ratio was essentially constant throughout the process of coring.

An even more conclusive result was obtained in diatomaceous mud at a depth of 2400 feet. The resulting core was 66 inches long with a penetration of 119 inches. Data on core-length and penetration at 27 points were obtained (Fig. 12) showing very clearly the presence of nearly equal increments of core per unit of penetration throughout the entire distance of penetration.

INTERPRETATION OF EXPERIMENTAL RESULTS

In the coring experiments, it was observed that lengthening of the core continued throughout the entire distance of penetration except in a few instances in which the limitations of experimental methods were apparent. The length of increments per unit of penetration, however, was dependent on the sediment cored. Small-scale experiments made in clay having the same water content at all depths showed that the core increments became smaller as the core became longer. On the other hand, experiments in mud, which had been deposited recently by natural agencies, showed that increments of approximately the same size were added to the core per unit of penetration regardless of the length of the core or the depth of penetration. In normal muds like those in which the latter experiments were made, the water content decreases with depth of burial when the grain size remains constant. The difference in behavior may be understood better by briefly reviewing the process by which cores are taken.

As the corer strikes the sediment surface, it has a certain amount of kinetic energy. This energy is expended in overcoming outside wall friction of the tube, friction between the mud core and the inside wall of the tube, and resistance of the mud toward being pushed aside or down warped at the lower end of the tube. While the core is short, it offers little resistance toward being pushed farther into the tube. As the same time, however, the mud at the nose is easily pushed aside or down warped so that only part of it enters the tube. When the core becomes longer, more force is required to push it against the increased frictional resistance. In order for equal increments to be added to the core at depth, the resistance of the mud against being pushed aside or down warped must also increase.

In a mud having uniform plasticity (as indicated by uniform water content and grain-size) the resistance of layers toward being down warped

and thinned increases only slightly with depth; and accordingly, smaller increments are added to the cores as they become longer. An example of this type of shortening is given by the small-scale cores taken in the box of colored clay layers (Fig. 7). A similar type of shortening has been reported in the case of a core tube driven into Pleistocene varved sediments (Piggot, C. S., personal communication). Although no data as to water content or grain size of the latter sediment are available, it is probable that the material is reasonably uniform with depth since it is not being deposited at present. Similarly, experimental cores taken by Pratje definitely showed a decrease in size of core increments with increasing depth of penetration (Pratje, 1934). In this instance, the water content was found to range from 50% at the mud surface to 68% at the bottom of the cores. Because of this very considerable increase in water content, the mud at depth may have been less viscous than the surface mud and thus may have offered less resistance toward being pushed aside or downwarped by the partly filled core-tube.

Ordinarily, the mud toward the bottom of the penetration is not so easily downwarped as is the mud near the surface because the lower water content of the former gives less lubrication for movement, i.e., is more viscous. Apparently this factor is sufficient to balance the increase in friction between the core and the tube, and therefore all increments added to the core are about the same size per unit of penetration. Thus in the seven photographic experiments and the two others made under water, the length of the core at any instant was found to be approximately in direct proportion to the depth of penetration at that instant (Figs. 9, 10, 12).

The mechanical pushing aside or downwarping of part of the sediment near the nose of the instrument is usually not sufficient to destroy laminae (Pl. 2, fig. 2). However, interesting injections of material have been observed at boundaries between different types of sediment. Wrath reports similar contamination in some experimental cores (1936). Friction of the tube wall against mud cores produces a layer of smeared material generally not more than about 1/32 inch thick, and in several cores so thin that it failed to conceal the presence of thin laminations in the core.

RELATION OF SHORTENING TO STUDY OF CORE SAMPLES

The linear relationship between the position of a sample in a core and the depth at which it lay in the undisturbed sediment (Figs. 8-10, 12) is important in the interpretation of marine cores. For example, if total penetration is 8 feet and a core is 4 feet in length, a sample lying at a depth of 3 feet in the core should be considered as occurring at a depth

of 6 feet in the undisturbed sediment. The significance of such a relationship is readily apparent in the calculation of the rate of deposition of sediment based on the depth in cores at which changes in types of sediment or changes in fauna occur.

As an illustration, Schott found that in seven red-clay cores taken in the equatorial Atlantic Ocean a faunal change occurred which could be correlated with the end of the glacial period (Schott, 1935, p. 120-130). Assuming that this faunal change, which occurred at an average depth of 17.14 cm. in the seven cores, took place about 20,000 years ago, Schott was able to derive an average rate of deposition for the red clay amounting to 0.86 cm. per 1000 years. However, no allowance was made for shortening. According to Pratje (1935, p. 25), the average ratio of core-length to penetration for the Meteor red clay cores was 59.4%. If core-shortening occurred in a manner similar to that shown in Figures 8, 9, 10, and 12, the average rate of deposition for the red clays examined by Schott is probably more nearly 1.45 cm. in 1000 years; 1.45 cm. at least represents a maximum rate and 0.86 cm. a minimum for these cores.

Interpretations of cores taken by Piggot across the North Atlantic (Bramlette and Bradley, 1940) may also be greatly influenced by the manner in which shortening is assumed to occur. No exact data concerning depths of penetration have been published. Quite different pictures of the relative lengths of time represented by the alternating layers of glacial-marine deposits and foraminiferal ooze would be obtained, depending on whether shortening occurred in the manner shown in Figure 7 or in Figures 8, 9, 10, 12. The latter type of shortening seems far more probable.

SUMMARY AND CONCLUSIONS

A large coring device which derives its energy from its weight and the velocity with which it strikes bottom was developed for investigations of submarine geology. The apparatus consists essentially of a shaft on which is mounted a streamlined mass of lead; a valve which permits only upward passage of water within the device; and a core-tube which retains a core after being pushed into the bottom sediment.

The corer has been used successfully in depths as great as 12,200 feet. Many of the cores obtained are far longer than those taken by any other type. Cores in fine-grained sediments range up to 16 feet 9 inches in length and average 6 feet 3 inches. Sand was found more difficult to core. Sampling was not confined to sediments, however, since small rock chips or pebbles were recovered in a number of cores.

It was observed that the core-length varied from 40 to 70 per cent of the depth of penetration. However, coring in layered sediments, measure-

ments made while the corer was being hammered or pushed into mud, photographic studies of the process of coring, and finally sea-floor experiments showed that the core becomes longer throughout the entire period of penetration. For tests in mud having a normal decrease in water content with depth of burial, the increments added to the core per unit of penetration are nearly equal throughout the entire penetration. Other experiments indicate that this shortening is not due to compaction or squeezing of water from the sediments but that only part of each layer of sediment is added to the core while the remainder of the layer is pushed aside. Although with continued increase in length a core will finally become so long that it acts as a solid rod and pushes all the material of the lower layers aside, experiments show that such a length is greater than those obtained in the present writers' coring operations.

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University of Illinois, Urbana, Ill.; The Scripps Institution of Oceanography, La Jolla, Calif.
Manuscript received by the Secretary of the Society, June 26, 1940.
Read before the Geological Society, December 29, 1938.
Contributions from the Scripps Institution of Oceanography, New Series, No. 148.